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Maximizing profits for a commercial salmon rearing facility using linear programming

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MAXIMIZING PROFITS FOR A COMMERCIAL SALMON REARING FACILITY USING LINEAR PROGRAMMING

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THESIS

Maximizing Profits for a Commercial
Salmon Rearing Facility Using
Linear Programming

by

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December 1972

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ABSTRACT

A linear programming model of a commercial salmon rearing facility is formulated. A scheme is provided for facility expansion at an optimum rate, maximizing profit to the grower. The variables are the number of fish started in each year and the number of fresh water ponds and salt water pens to construct in each time interval. Constraints are the volumes of facilities required and provided. Cost constraints are included. The model provides the best course of action for facilities expansion based on current knowledge in the salmon mariculture field. The formulation provides for easy updating as technology advances.

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I. INTRODUCTION

The various species of Pacific salmon begin their natural life cycle by hatching in rivers and streams during the winter months. Depending on the species they normally spend from one to nineteen months in fresh water before they are biologically mature enough to migrate to sea where they spend the majority of their lives. As adults they once again return to the streams where they were hatched, to spawn and die.

As man systematically closed off spawning rivers and streams with dams and other barriers the salmon population began to dwindle. To offset encroachments on natural spawning grounds, various governmental agencies began to open salmon hatcheries, the first one being in operation prior to the beginning of the twentieth century. With the passage of time, proficiency and technology have grown so that artificial spawning and hatching techniques are today both well defined and in wide use. Indeed, perhaps more is known today of salmon hatching and fresh water rearing than of any other fish.

Until the close of the 1960's, artificial salmon rearing was strictly a governmental function. This was physically due to both the relative expense and reasonably high mortalities of the fish. In addition, legislation forbade private growers. Minimum size restrictions were also placed on

commercial and sport caught fish. These factors restricted the salmon harvest to adult fish, after they had spent a good portion of their lives in salt water.

With improved technology in the mid-1960's, primarily in the form of a better fish food, and more effective antibiotics for controlling diseases, the cost of rearing salmon, at least in fresh water, dropped sharply. Similarly, the risk from disease began to lessen with new drugs. These advances were soon noted by commercial interests.

In July 1969, the National Marine Fisheries Service (NMFS) began a preliminary feasibility study for captivly rearing marketable coho salmon in salt water. These fish had completed their fresh water portion of their life pattern and had "smolted," or become biologically ready to enter salt water.

In November 1970 Ocean Systems, Incorporated (OSI) began a pilot study to determine if the NMFS study results could be applied successfully on a commercial scale. The results were encouraging.

Based on the success of the NMFS and OSI studies, and the fresh water rearing advances mentioned earlier, the State of Washington enacted necessary legislation[1] in 1971 to permit commercial rearing of salmon. Guidelines for

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[1]Senate Bill 142 (Chapter 35, Laws of 1971), State of Washington.

salmon aquaculture were subsequently issued by the Washington State Department of Fisheries.[2]

A marketing study for "plate-sized salmon" was successfully completed by OSI and in January 1972 Downsea Farms was incorporated to begin salmon rearing on a commercial scale. The stage had been set for construction of a detailed analytical model for expansion of a commercial facility.

The purpose of this paper is to explore an optimal expansion pattern for commercial salmon rearing based on data and experiences of the Hatcheries Division of the Washington State Department of Fisheries and the OSI and NMFS feasibility studies. A ten year period of expansion is analyzed using basic linear programming techniques. The objective of such a model is to predict the effects of various production techniques on overall profit. This is desirable since in the actual production phase there is seldom room for a "second chance" to correct for a bad guess, while the results of several approaches can be inexpensively analyzed with a mathematical model. Optimal long term resource allocations are easily derived from such a model for any desired set of input assumptions.

The model considers the physical requirements of rearing fish and allows normally occurring physical bounds to

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[2]"Policies and Procedures Pertaining to Salmon Aquaculture in the State of Washington," Washington State Department of Fisheries, 2 February 1972.

be entered. Provisions are made for hatching, fresh and salt water rearing, harvesting marketable fish and rearing of brood stocks. Maintenance of a brood stock is required by the Washington State Department of Fisheries. Overriding constraints such as market magnitude, total salt water space, and fresh water volume are considered.

Specifically, a unit quantity of fish is traced through the facility. Eggs are incubated and space and cost allocations are made based on the expected number of survivors at each stage.

The current species considered are coho and fall chinook salmon. This is done in light of current technology. Other species could be easily incorporated into a simple reformulation of the model, however.

II. PHYSICAL REQUIREMENTS OF A SALMON HATCHERY

Site selection is critical in the development of a commercial operation such as this. This section provides a qualitative overview of the physical requirements and is not intended to be analytic. The following issues must be diligently investigated by any group interested in developing a commercial operation.

Water quality is the overriding consideration in site selection. Sufficient flow must be maintained through the ponds or pens to provide adequate oxygen.

Water temperatures must be maintained above 40°F., or the fish will not feed well. Temperatures above 60°F. are accompanied by diseases and intollerably high mortalities.

A number of diseases[3] are known to infect salmon and recent research has proven most to be controllable. Among the most common salmon diseases are furunculosis, bacterial gill disease, kidney disease, low temperature disease and vibriosis. "Gas bubble" disease and "bum-eye" disease aren't true diseases but will be discussed in this section.

Furunculosis occurs principally in fresh water when weekly average water temperatures run consistently above

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[3]"Diseases of Pacific Salmon - Their Prevention and Treatment," State of Washington, Department of Fisheries, Hatchery Division, James Wood, June 1968.

56°F., but has been recorded with temperatures as low as 35°F. Furunculosis is most easily prevented by limiting the migration of wild salmon stocks past the hatchery. Decaying adult salmon carcasses upstream will spread the disease downstream. Excessive crowding should be avoided a month prior to annual summertime infestations. Total losses are rarely above 10% and tend to be self-limiting.

Bacterial gill disease results from a shortage of pantothetic acid and has been known to create losses of up to 20% in a single day. Most outbreaks occur when fish are still small and pond loadings exceed 1/2 pound of fish per cubic foot.

Low temperature disease usually affects only young fish that have been ponded less than two weeks. Very young fish have suffered losses up to 50%. Once past the first two weeks, losses rarely exceed 20%.

Kidney disease is caused primarily by excessive decaying carcasses upstream and can be controlled by limiting the wild stock migration.

Gas bubble disease is caused by super-saturation of gasses in the water supply. Nitrogen is the least tolerated of the gasses. Frequent causes of nitrogen super-saturation are air being sucked into a pump, waterfall plunge pools, and air domes if springs or wells are used for a water supply. Table I shows the effects of excessive dissolved nitrogen as a function of fish size.

Table I

Effects of Nitrogen Saturation on Salmon

Fish size	% Saturation	Effect
Advanced yolk-sac, buttoned up fry	103-104%	death
Fingerlings and yearlings	105-112%	blindness
	113%	death
Adult	118%	eye damage

"Bum-eye" disease results from overcrowding. The resulting tension causes the fish to pick out each others' eyes.

The above diseases are most commonly found in fresh water and in most cases adequate prophylaxes have been discovered and are in common use.

Excessive silt in the water supply will cause suffocation of unhatched eggs and must also be guarded against through selection of the water source.

Vibriosis affects all species of salmon in salt water, with pink and chum salmon being the most susceptible. Commonly, outbreaks are found in water over 50°F with strong outbreaks being recorded in water temperatures above 60°F. Stressed fish are most susceptible. Vibriosis is controlled by using medicated feed through the warmer months.

The minimum oxygen content of both fresh and salt water is about 4 milligrams per liter for salmon survival.

In a "standard" 6900 cubic foot hatchery pond this dictates a water supply of about 600 gallons per minute if the pond is loaded near capacity. More flow is detrimental as it will tumble the fish or cause them to expend too much effort swimming against the current, with weaker fish being lost. In a large half acre pond as much as 12 to 15 cubic feet per second may be required. Water is seldom reused because the expense of aerating and sterilizing the water for reuse almost doubles the cost of the fresh water facility.

Salt water oxygen requirements are similar to those of fresh water. The 3/4 inch nylon webb pens currently used may tend to foul with marine plants and animals, reducing the oxygen supply. To counter this, the pens must be periodically removed, dried, and hosed down. A bloom of jellyfish could be disastrous in the salt water phase, completely blanketing the pens. Although a continuous current flow is desirable, slack water is common twice daily in Puget Sound and must be accounted for. In reality, however, the water rarely slows below 1/4 knot. Currents up to 3 knots are acceptable.[4]

Salt water site selection is also governed by surface wave action, and a bay sheltered from prevailing winds and storms is strongly desired.

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[4]"To Market, to Market, to Buy a Small Salmon," Pacific Northwest SEA, Winter 1972, Vol. 5, No. 1, p. 7.

Some space ashore should be allocated to equipment and feed storage.

III. DISCUSSION OF DATA

A model such as this requires the collection of quality data on all facets of the operation before a solution can be meaningful. Fecundity (reproductivity) of brood stocks, incubation periods, growth rates, facilities requirements, expected mortalities, and comprehensive cost data must all be assembled. Obviously, the more accurate the inputs, the more confidence one will have in a solution.

Fecundity was calculated by examining the records of eleven Puget Sound Washington State hatcheries over a five year period. The number of females spawned and the number of eggs obtained resulted in Table A-I. Fall chinook females averaged 4652 eggs while coho females averaged 2903 eggs. Space was allocated for brood stock based on the number of adults required to ensure a unit 100,000 eggs. One male was kept for every two females.

This method of computing the number of captively reared brood fish based on fecundity of wild stocks could prove hazardous, however, since it is not known if captive fish will be as prolific as their wild cousins. Fortunately, one is allowed to purchase eggs from the State of Washington through the first six years of a commercial operation while accurate data is being obtained. Currently the effects of captive rearing on fecundity are not known.

Incubation periods are a function of water temperature units (cumulative day-degrees Fahrenheit above 32°F.). Fall chinook are normally ponded after about 1650 temperature units and coho after about 950 T.U. Using heated water, one can predict ponding dates with reasonable accuracy. Fall chinook can thus be ponded in early to mid January and coho in late January to early February. If one relied on unheated spring or river water, ponding dates of late April for coho would not be uncommon. This much variability would make efficient management very difficult at best.

Salmon growth rates are a complex function of several variables. Among these are water temperature, water volume, pond loading, dissolved gasses present in the water supply, current, size of the fish, initial egg size, feeding procedures, feed type and resident diseases. It would be difficult at best to define a time-dependent function of all the above variables, particularly since research has not been even attempted to isolate the independent effects of most of them in large scale facilities. Salmonids have, however, been successfully reared for many years in fresh water. With no more detailed information available, the best approach is to use growth data from hatcheries with environments nearly identical to those anticipated in a commercial venture.

The most significant change in growth rates in recent years occurred with the introduction of Oregon Moist

Pellet feed in the early 1960's. With the new feed came the concept of rearing particularly fall chinook at the most rapid rate possible until they smolted in their first spring. Increased size at release into salt water brought higher survival rates. Coho, on the other hand tended to grow faster than desired if fed as much as they would eat, so the objective of most hatcheries is currently to rear coho at a slower than possible rate.

In rearing salmon commercially, two factors bear heavily on an objective to put weight on the fish as rapidly as possible. First, less labor and feed costs are incurred. Each extra day a fish remains swimming costs in terms of body maintenance calories which must be replaced by additional feed. Secondly, the highest incidence of disease occurs when water temperatures are above 60°F. in late summer and when ponds or pens are heavily loaded.

The Washington State hatchery system method of rearing fall chinook at a very rapid rate coincides with the commercial objective. The water quality found at two western Washington hatcheries corresponds quite closely with that used by the OSI pilot study. Since the steady-state commercial operation would in all likelihood match quite closely the conditions found at Minter Creek and George Adams hatcheries, growth data from these hatcheries is used.

In the case of coho salmon, only in "brood year 1967" (1967-1968) at Cowlitz Hatchery were coho reared at an accelerated rate comparable to the pilot study. Cowlitz

is the world's largest salmon hatchery, however, and much useful data was obtained from that experience. The data is treated in similar form to the fall chinook data. Fisheries biologists in the Department of Fisheries felt the Cowlitz growth rate could readily be duplicated in Minter or George Adams hatcheries since the conditions are not significantly dissimilar. Water heating would be required, however, to reach the 50°F. optimum. Water temperatures for fresh water observations used in this paper are shown in Table A-II.

Determining average fish size can be a problem. Usually weekly samples of fish are taken, weighed, and counted. An accurate sample is difficult to obtain in any hatchery, however, since the larger fish tend also to be stronger and tend to escape the sampler. Thus, samples tend to be biased toward the smaller fish. Indeed, one fisheries biologist systematically removed all the sampled fish from a pond as he sampled them and found a direct relationship between average sample size and number of fish removed. The largest fish were, as expected, the last to be caught.

Due to inherent sampling errors mentioned above and the fact that the OSI fresh water phase was conducted in two large, deep dirt ponds, fresh water growth data was taken from State records. In a State hatchery, where the fish are more readily observed by a superintendent with many years of experience, the data tends to be more reliable.

In the model, both early and late spawning fall chinook and coho are considered. Hatchery fish are frequently mixed by starting date and it is impossible to differentiate between early starters and late starters after several months of rearing. It is known that fish tend to grow slower in colder water, but this could not be shown from the available homogeneous data. In this model two groups were started three weeks apart. No difference in growth rates was credited to the early and late starters, however. Those minor differences should properly be incorporated as data becomes available.

Expected mortalities are computed both from the State hatchery records mentioned above and from the NMFS report. Expected numbers of surviving fish per 100,000 eggs started is shown in Table II.

Operating cost data was taken from the NMFS study[5] and linearly scaled to 100,000 starting fish and NMFS study expected mortalities in fresh and salt water. It was also scaled to match mortalities of the State hatcheries in fresh water. It is felt that a young corporation would, due to lack of experience, probably start with mortalities on the order of the NMFS study and gradually approach those in the State hatcheries. Labor, feed and maintenance costs were all taken from the NMFS study as no other data

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[5]"Economic Feasibility of Salmon Mariculture, Preliminary Analysis," Richards, Mahnken, Tanonaka, NMFS, Feb. 1972.

Table II

Expected Survivors of 100,000 Salmon Eggs Incubated

System	Coho State	Coho OSI/NMFS	Fall Chinook State	Fall Chinook OSI/NMFS[6]
Incubation	91300	91300	91300	91300
Fry-Fingerling	83083	76692	89017	78518
Harvest	63253[6]	58516	66832[7]	58516
Start Brood Stock	53.8[8]		33.5[8]	
End Brood Year I	43.1		26.9	
End Brood Year II	34.4		21.5	

has been isolated specifically by fish species. Fall chinook data was extrapolated based on coho costs. With additional experience, costs may change somewhat.

Construction costs for salt water facilities were obtained from Mr. Jon Lindberg, vice president of OSI and director of Domsea.

Construction costs of fresh water facilities were taken from the preliminary estimates for constructing

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[6]It is assummed that chinook mortalities will occur at least at the rate of coho mortalities. These figures are conservative, therefore, since fall chinook take longer to reach marketable size and are therefore subject to disease longer.

[7]The salt water mortality rate of the NMFS feasibility study is assigned to fresh water mortalities found in George Adams and Minter Creek hatcheries.

[8]An assummed mortality rate of 20% per year is assigned to brood fish. These figures provide for an expected 100,000 eggs per species at the end of brood year II.

Humptulips Hatchery in 1974. Since Domsea has leased facilities up until this time, it is felt that a reasonably accurate picture of hatchery costs would be best obtained from the State of Washington.

IV. GROWTH CALCULATIONS AND FACILITIES REQUIREMENTS

Growth rates for fall chinook were computed from three years of observations at both George Adams and Minter Creek hatcheries. The number of days reared was regressed against both the natural log of the number of fish per pound and against the number of fish per pound. Data from the first twenty days after ponding was omitted because in this period fish feed poorly and therefore show very little growth.

Scatter diagrams for all regressions are shown in Tables B-I through B-XVIII, along with other statistical information. The correlation coefficients are shown in Table III. Correlation coefficients for days reared versus Ln (fish weight) are in every case considerably higher than for the days versus fish weight correlations. This indicates that a logarithmic model of salmon growth rate is more accurate than a linear model.

Coho growth rate was computed in much the same manner as fall chinook. The statistical results also showed days reared minus the first twenty days versus the natural log of fish weight as the best model of growth rate.

Tables B-V, B-VIII, V-XIV, and B-XVII show the appropriate scatter diagrams and regression lines for both fresh and salt water growth data.

Graphs I and II summarize the above growth curves.

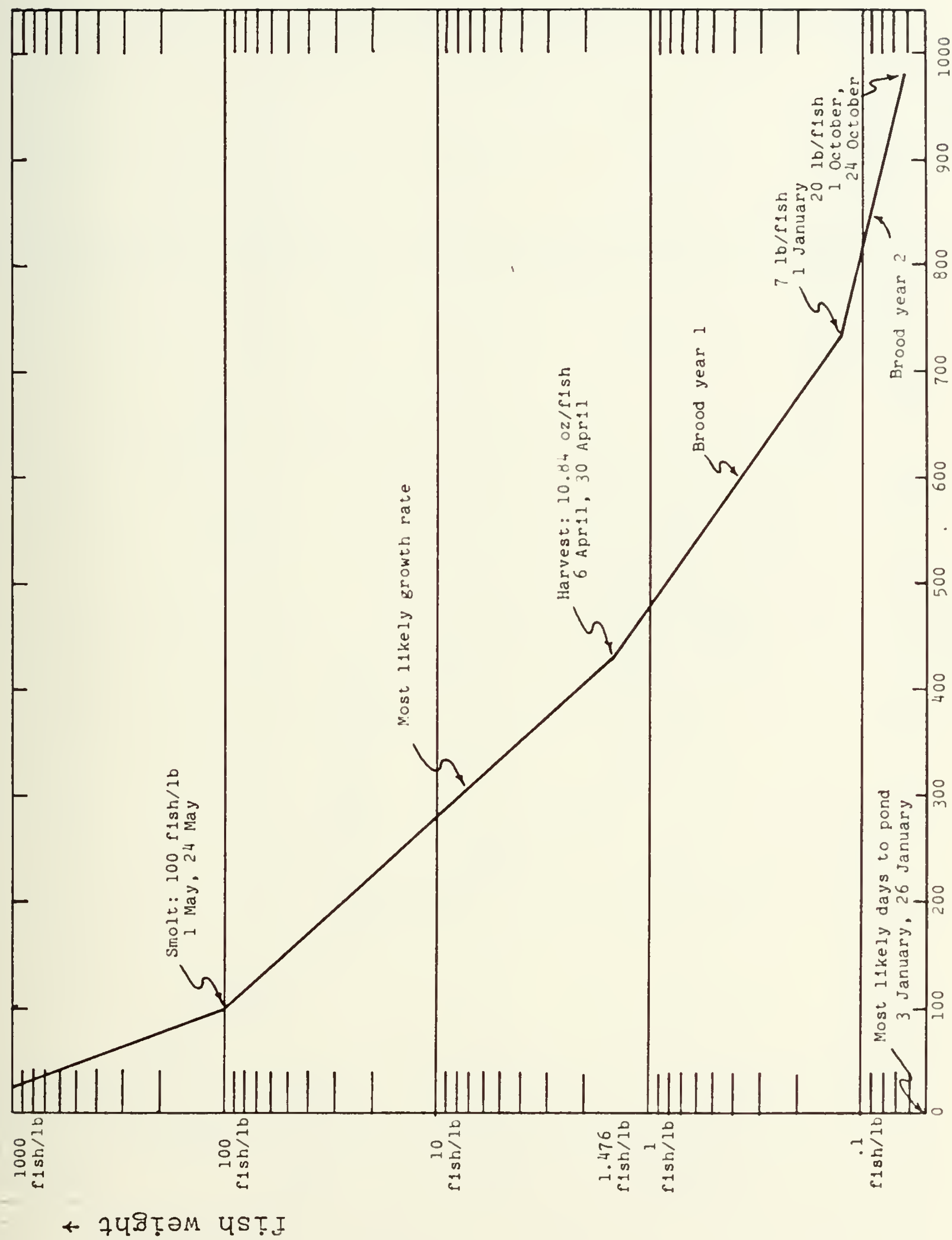
Table III

Growth Data Statistics

		Fresh water days 0-20 omitted Correlation Coefficient	Complete data, all days included Correlation Coefficient
Coho Fresh Water	(1)	-.8722	-.8981
	(2)	-.9878	-.9911
Coho Salt Water	(1)		-.9202
	(2)		-.9820
Fall Chinook Fresh Water	(1)	-.9217	-.9552
	(2)	-.9491	-.9552
Fall Chinook Salt Water	(1)		-.8006
	(2)		-.9634

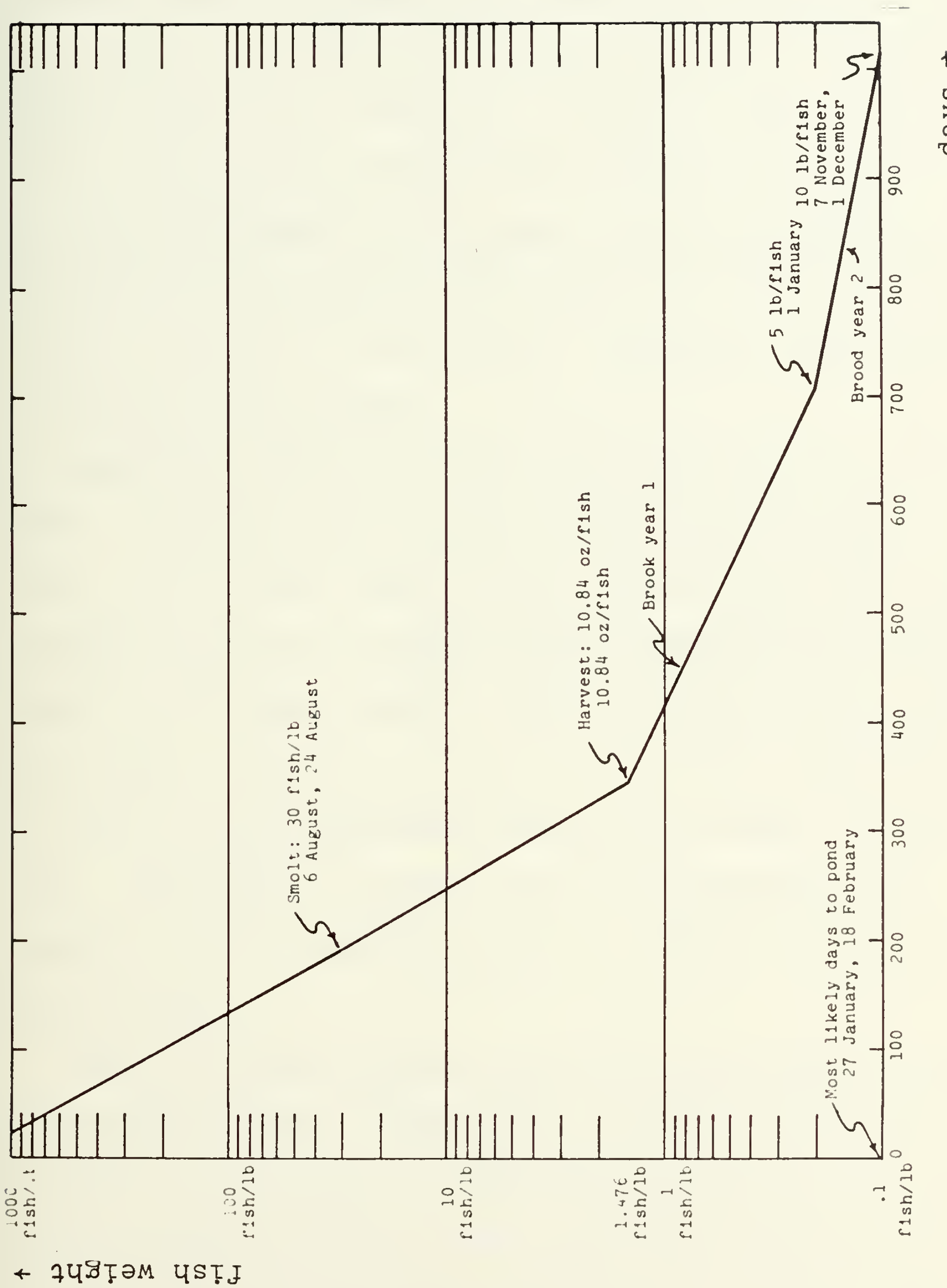
(1) # Fish/lb vs days reared

(2) Ln (# fish/lb) vs days reared



Graph I

Fall Chinook Growth Curve



Graph II

Coho Growth Curve

In any mixed species hatchery it is desirable to have the hatchery filled to capacity as much of the time as possible. This is accomplished normally by allocating the maximum amount of space to be required by each starting group from the time it is initially ponded until the first departure date for some group. When one group of fish has been removed, space then becomes available to spread out the remaining groups until some other group departs. The process is repeated until all groups have been removed from that portion of the system. The same concept applies in the salt water phase.

Departure dates are termed "critical dates" in this model. Critical dates occur for fall chinook when they reach 100 fish per pound in fresh water, since this is a rough milestone for their having smolted and become ready to enter salt water. Coho are considered as smolted at 30 fish per pound in this model. Once in salt water, all the fish are harvested when they averaged 10.8 ounces each. Brood stock critical dates are determined as 1 January, and the spawning dates to complete their appropriate cycles.

Table IV shows critical dates for fall chinook and coho salmon based on regressions previously discussed for the fresh water phase, Domsea data from entry into salt water to harvest, and a "best guess" for the brood phase. The brood phase guesstimate was based on average adult size and a logarithmic growth rate. Since salmon have

Table IV

Space Allocation Matrix Format Showing

Number of Days Reared and Number of Fish per Pound

Fresh Water

Fall Chinook #1	Fall Chinook #2	Coho #1	Coho #2	Critical Dates	Water Temp.
				3 Jan	42.6
				26 Jan	42.9
				27 Jan	42.9
				18 Feb	44.3
100 fish/lb 97 days	211 fish/lb 74 days	327 fish/lb 74 days	498 fish/lb 52 days	11 Apr	50.3
	100 fish/lb 97 days	211 fish/lb 96 days	327 fish/lb 74 days	3 May	50.1
		30 fish/lb 196 days	46.5 fish/lb 174 days	11 Aug	55.2
			30 fish/lb 196 days	4 Sept	54.5

Year i, i=1,...,10

Salt Water to Harvest

Fall Chinook #1	Fall Chinook #2	Coho #1	Coho #2	Critical Dates	Water Temp.
				11 Apr	50
				3 May	51
				11 Aug	58
				4 Sept	53
20.7 fish/lb 291 days	26.6 fish/lb 268 days	1.476 fish/lb 345 days	2.25 fish/lb 324 days	20 Nov	50
16.3 fish/lb 312 days	21.1 fish/lb 289 days		1.476 fish/lb 345 days	10 Dec	48
1.476 fish/lb 429 days	5.70 fish/lb 406 days			6 Apr	45.8
	1.476 fish/lb 429 days			30 Apr	47.5

Table IV-cont. <u>Brood Stock</u>

Fall Chinook #1	Fall Chinook #2	Coho#1	Coho#2	
				20 Nov
				10 Dec
				6 Apr
				30 Apr
.146 fish/lb 732 days	.12 fish/lb 708 days	.2 fish/lb 702 days	.19 fish/lb 723 days	1 Jan
.05 fish/lb 980 days	.06 fish/lb 957 days	.11 fish/lb 973 days	.116 fish/lb 950 days	1 Oct
	.05 fish/lb 980 days	.105 fish/lb 997 days	.11 fish/lb 974 days	24 Oct
		.1 fish/lb 1011 days	.105 fish/lb 990 days	7 Nov
			.1 fish/lb 1011 days	1 Dec

Year i, i=1,...,10

never been reared to brood size in quantity, both these estimates must be revised as data becomes available. This illustration is key since it is the common framework for allocating space, once growth rates are determined.

In the interest of efficiency, account was made of the expected mortalities. Sufficient space was made available only for the expected number of surviving fish at each critical date. Expected mortalities in fresh water were computed for both the State hatchery system and that suggested by the National Marine Fisheries Service. Chinook mortalities were considered to be the same as coho mortalities in the NMFS figures. Strictly NMFS coho mortality rates were used in the salt water phase up to harvest since no other data was available. Twenty percent mortalities per year were assummed for brood stock. Tables V and VI summarize expected mortalities for fall chinook and coho, respectively.

Temperature data was recorded as a function of age of the respective fish sampled. A summary is presented in Table A-II.

The most complete study to date of water requirements of salmonids was done by Mr. Paul Liao.[9] In it, he describes maximum hatchery loading as a function of oxygen uptake rates, water temperature, fish size, hatchery

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[9]Liao, Paul B., "Water Requirements of Salmonids," <u>The Progressive Fish-Culturist</u>, Vol. 33, No. 4, October 1971, pp. 212, 221.

Table V

Fall Chinook Mortalities

Days Reared		Expected Cumulative Mortalities State	NMFS	Water Temp
		(Expected Survivors)		
Start Incubation		100,000 eggs	100,000 eggs	
At Ponding (0 Days)		91,300 fish	91,300 fish	
Group I	Group II			
	74	89,474	79,157	50.34
97		89,119	78,518	50.34
	97	89,017	78,518	50.05
	268	69,433	61,743	50
	289	68,632	61,030	48
291		68,365	60,793	50
312		68,098	60,793	48
	406	67,208	59,764	45.8
429		67,083	59,045	45.8
	429	67,083	59,045	47.5

Table VI

Coho Mortalities

		Expected Cumulative Mortalities		
Days Reared		State	NMFS	Water Temp
		(Expected Survivors)		
Start Incubation		100,000 eggs	100,000 eggs	
At Ponding (0 Days)		91,300	91,300	
Group I	Group II			
	52	85,557	81,074	50.34
74		84,361	79,157	50.34
	74	84,361	79,157	50.05
96		83,996	78,358	50.05
	174	83,083	76,200	55.16
196		82,900	76,692	55.16
	196	82,900	76,692	54.50
	324	63,418	58,669	50
345		63,253	58,516	50
	345	63,253	58,516	48

elevation, and water flow rate. The following relations were defined:

(1) Oxygen uptake rate

$O_2 = KT^nW^m$, and

T	K	m	n
T≤50°F	7.2×10^{-7}	-.194	3.20
T>50°F	4.9×10^{-5}	-.194	2.120

(2) Oxygen content of water in milligrams O_2/liter

$$C_e = \frac{S(132)}{T^{0.625}} \cdot \frac{760}{760 + \frac{E}{32.8}}$$

(3) Loading factor in lbs of fish/gpm flow

$$Q = \frac{1.2(C_e - C)}{O_2}$$

where

O_2 = Oxygen uptake rate in lbs. O_2/100 lbs fish/day

K = Rate constant

T = Water temperature in degrees Fahrenheit

W = fish size lb/fish

$$m = \frac{\log \frac{O_2}{O_1}}{\log \frac{W_2}{W_1}}$$ = function of change in oxygen uptake rate with change in fish weight

$$n = \frac{\log \frac{O_2}{O_1}}{\log \frac{T_2}{T_1}}$$ = function of change in oxygen uptake rate with change in temperature

$K = \frac{0}{T^n}$

C_e = dissolved oxygen concentration in milligrams per liter at water temperature T and elevation E

S = Saturation factor of dissolved oxygen

T = Water temperature in degrees Fahrenheit

E = Elevation in feet

Q = Carrying capacity in lbs. fish/gallon per minute

C = Minimum dissolved oxygen concentration in milligrams per liter.

Assumming a hatchery elevation of 200 feet, 100 percent dissolved oxygen concentration at inlet, minimum dissolved oxygen concentration $\geq$ 4 milligrams per liter at outlet, and 600 gallons per minute water flow, and average temperature data recorded at Minter Creek and Adams hatcheries, volume requirements for expected numbers of surviving fish were calculated for each critical point in the hatchery schedule. The formula used to compute volume requirements for the fish remaining per 100,000 eggs started was:

was:

$$\text{Cubic feet} = \frac{(100{,}000 - \text{cumulative mortalities})}{(\#\text{fish/lb})\left(\frac{600 \text{ gpm max.}}{6900 \text{ ft}^3}\right) \cdot Q}$$

Mr. Liao's formulation was used to compute volume requirements in fresh water for both Washington State hatchery expected mortalities and for those assummed by

the NMFS study.[10] In salt water the NMFS mortalities were used exclusively since no Washington State data exists. Since the size of the brood fish extends beyond Mr. Liao's study, assumptions of twenty percent mortality per year and maximum loading of 3/4 pound of fish per cubic foot were made when his formulae were applied to brood stocks. In no case were fish loaded beyond the widely accepted maximum of two pounds of fish per cubic foot.

Table VII illustrates the space requirements calculated with Liao's method for both Washington State mortality expectations and those of NMFS, as discussed earlier.

Dr. Peter Bergman, Washington State Department of Fisheries constructed a table of maximum fresh water pond loadings for use by State hatcherymen, which is included in Table B-XIX. The table was the result of an extensive survey of the State's most experienced hatcherymen. The table shows loadings for fall chinook and coho as a function of water flow, temperature and fish size.[11] Dr. Bergman's table was converted to maximum pounds of fish per cubic foot. These results are shown in Table B-XX. Table B-XX was converted to the graphs of maximum pond

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[10]"Economic Feasibility of Salmon Mariculture, Preliminary Analysis," Richards, Mahnken, Tononaka, National Marine Fisheries Service, February 1972.

[11]A similar table was computed from Liao's computations and is shown for comparison in Appendix A

Table VII

Volume Requirement Matrix Entries

Feet^3 Required for Surviving Fish in Fresh Water

Applying Bergman Table

State Mortalities FC#1	FC#2	Coho#1	Coho#2	NMFS Mortalities FC#1	FC#2	Coho#1	Coho#2	Date	Water Temp.
								3 Jan	42.64
								26 Jan	42.87
								27 Jan	42.87
								18 Feb	44.27
2132.0	1229.1	697.3	512.8	2090.7	1205.9	654.3	485.9	11 Apr	50.34
	2121.9	925.8	697.3		2080.7	863.7	654.3	3 May	50.05
		2636.8	2320.4			2439.3	2128.2	11 Aug	55.16
			2570.5				2378.0	4 Sept	54.50

Year i, i=1,...,10

Applying Liao Formula

State FC#1	FC#2	Coho#1	Coho#2	NMFS FC#1	FC#2	Coho#1	Coho#2	Date	Water Temp.
								3 Jan	42.64
								26 Jan	42.87
								27 Jan	42.87
								18 Feb	44.27
567.1	311.9	206.6	149.3	556.1	306.0	193.9	141.46	11 Apr	50.34
	557.1	287.6	203.0		546.3	268.3	190.4	3 May	50.05
		1849.0	1301.6			1710.5	1193.8	11 Aug	55.16
			1780.9				1647.6	4 Sept	54.50

Year i, i=1,...,10

Table VII - cont.

Feet^3 Required for Surviving Fish in Salt Water

Applying Liao Formula

State Mortalities FC#1	State Mortalities FC#2	State Mortalities Coho#1	State Mortalities Coho#2	NMFS Mortalities FC#1	NMFS Mortalities FC#2	NMFS Mortalities Coho#1	NMFS Mortalities Coho#2	Date	Water Temp.
								11 Apr	50
								3 May	51
								11 Aug	58
								4 Sept	53
2795.4	2319.5	21708.2	15494.6	2741.5	2274.8	20082.5	14334.3	20 Nov	50
2817.1	2307.9		21427.2	2762.8	2261.5		19822.5	10 Dec	48
22699.9	5900.7			22262.5	5788.7			6 Apr	45.8
	22639.6				22203.3			30 Apr	47.5

Year i, i=1, 2, 3 (State Mortalities)

Year i+3, i=1,...,7 (NMFS Mortalities)

loading shown in Tables VIII and IX by assumming a flow rate of 600 gallons per minute. Maximum loadings for each group of fish at the various critical points were obtained by entering Tables VIII and IX at appropriate water temperatures and fish weights.

The results of the above calculations are shown in Table VII in matrix form.

For the convenience of the reader, Table B-XXI was computed. It shows values obtained from Liao's method in the format of Bergman's table. The comparison shows Liao loading a hatchery much more heavily than Bergman. This may be the result of Liao's not accounting for effects of disease in heavy loading and may be the result of only considering one specie of salmon. His paper mentioned neither.

Table VIII

Coho Maximum Pond Loadings at 600 Gallons-per-Minute Flow (from Bergman Table)

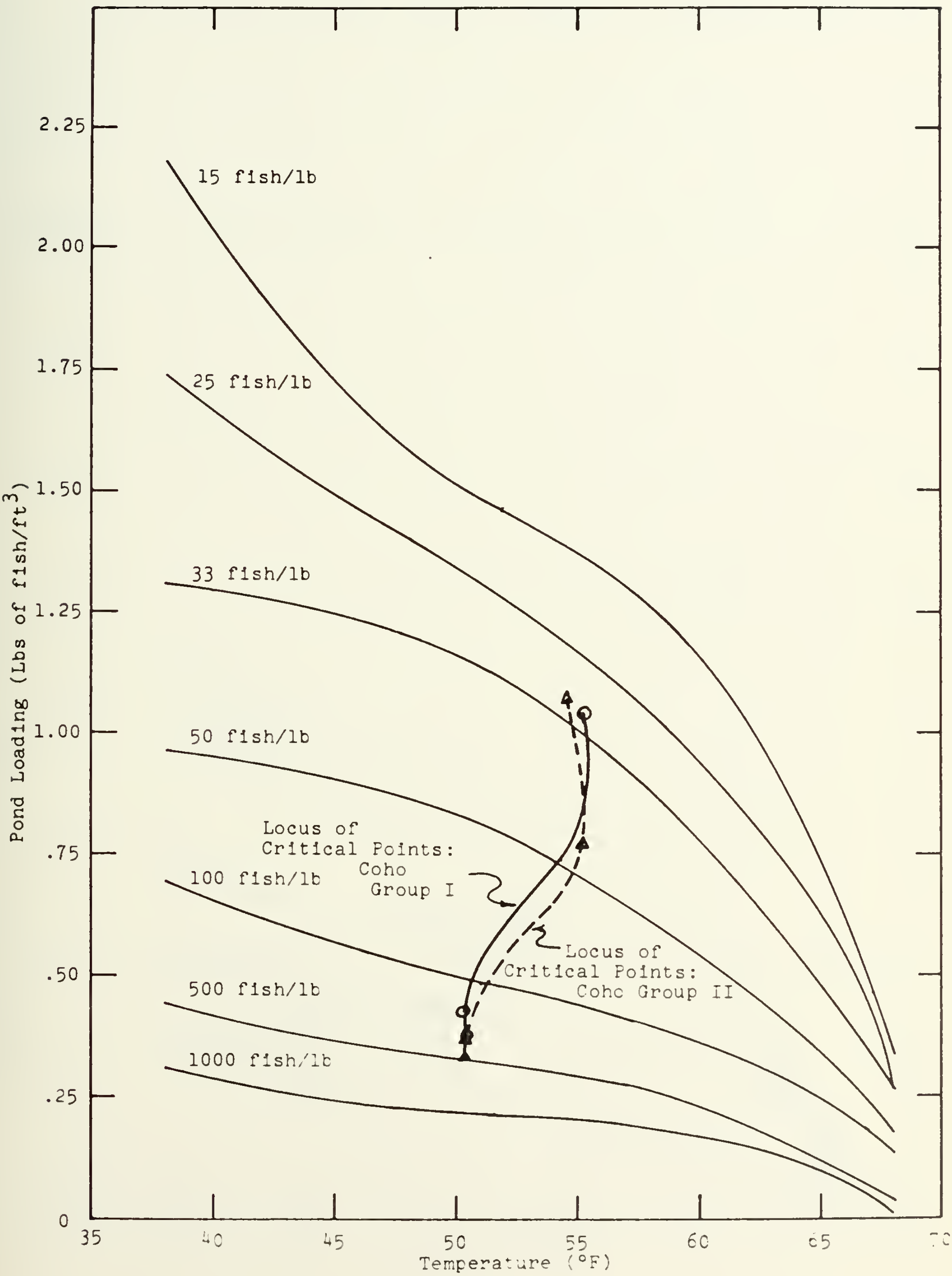
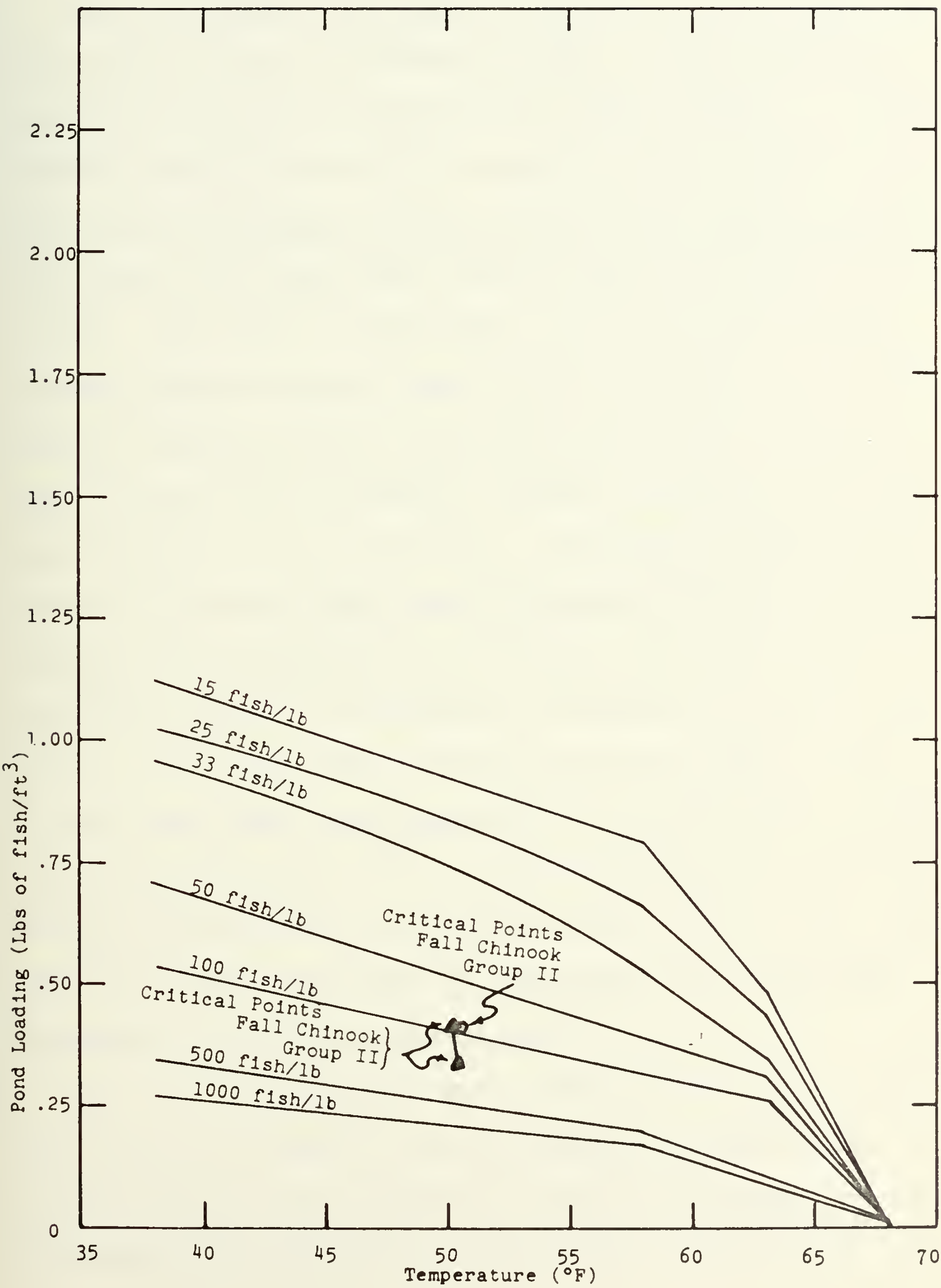


Table IX

Fall Chinook Maximum Pond Loadings at 600 Gallons-per-Minute Flow (from Bergman Table)



V. COSTING

With a program as young as commercial salmon mariculture, data on cost is tenuous at best. Since the NMFS feasibility study was based on the first attempt to rear salmon to marketable size in captivity on a commercial basis, cost estimates for salt water facilities and salt water, labor and feed costs are available only from this one source. The State of Washington has hatched and raised fingerling salmon since 1895, but an attempt has not been made at isolating labor, maintenance and feed costs by fish species, since typically several species are reared simultaneously in one hatchery. The State of Washington has, on the other hand, constructed many hatcheries over the past three quarters of a century and is the best available source of information on hatchery construction costs. The fresh water portion of the OSI pilot study, on the other hand, was conducted in a small rented existing fresh water facility. In the long run, however, such an activity would tend to be more flexible if the fresh water facilities were built by the corporation and the land purchased to fit the existing need.

For the above reason, fresh water facilities construction costs are based on the preliminary estimate for constructing the next Washington State Department of Fisheries salmon hatchery, "Humptulips." Salt water

facilities costs are based on current estimates by the pilot project managers.

Operating, maintenance and feed costs are derived from a study done by the National Marine Fisheries Service,[12] based on costs incurred in both the fresh and salt water phases of the pilot study. At present, this is the "best" data available. Obvious improvements can be made, particularly in labor expenditures, as more experience is gained. These improvements are discussed in a later portion of this section.

Humptulips salmon hatchery is currently planned for construction in 1974. Preliminary engineering estimates were completed in mid 1970. Obviously, any specific hatchery will have intrinsic "special case" costs dictated by its location. It must be anticipated that costs will vary somewhat as specific situations vary. The only modifications made here to the engineers' estimates are elimination of the holding ponds, and spawning ponds, the fishway and the rack across the water source. These all are normally used for adult fish that are returning for spawning, and are not required by a commercial firm. Adult fish will be spawned directly from salt water in the commercial operation as has been done many times in actual practice. The three standard residences are also

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[12] "Economic Feasibility of Salmon Mariculture, Preliminary Analysis," Richards, Mahnken, Tononaka, National Marine Fisheries Service, February 1972.

eliminated. Deletions were not made for piping associated with the above eliminated equipments. Table X shows the updated estimate.

Salt water construction cost estimates are based on figures from the first year of the Domsea pilot study as shown in Table XI. With such a limited data base and due to changing technology, these figures can be improved over time.

Operating, maintenance and feed (O, M and F) costs are based on the NMFS study, and as emphasized therein, could change with improved management and technology. O, M and F costs in Table II of the NMFS study were used directly, except rent of the fresh water site was omitted. The figures were scaled down from the 850,000 eggs started in the study to a unit 100,000 eggs. Initially, pilot study mortalities were used to compute Tables XII, XIII, XIV and XV. Heated water was assummed necessary through April to speed incubation and growth rates during the winter months. It was assummed that fall chinook and coho salmon would require equal amounts of food to achieve weights of 10.84 ounces per fish, while in fact the fall chinook would probably require more food simply because they are alive longer and more food value would be required to maintain body functions. Costs were pro-rated linearly when they overlapped ends of calendar years except in the case of feed for fall chinook. It was assummed that while in salt water fall chinook consume approximately half

Table X

Preliminary Cost Estimate for Humptulips Hatchery

(Modified as described)

		Cost	Hatchery volume
1.	Land	$ 40,000	
2.	Clearing 12 acres	$ 30,000	
3.	Remove unsuitable (25,200 yds.)	$ 37,800	
4.	Fill (80,000 yds)	$180,000	
5.	Mobilization (bid, bond, misc.)	$ 10,000	
6.	Pipelines - Gravity, 1400 Ft.- 12"	$ 13,440	
7.	Pipelines - Pump, 1200 Ft 36"27 cfs	$ 37,920	
8.	Intake, gravity	$ 18,000	
9.	Intake, pumping 3 pumps	$ 74,000	
10.	Road to gravity intake	$ 4,000	
11.	Road and dike to pump station (12,000 yds)	$ 27,300	
12.	Road and yard 2000 yds topping	$ 10,000	
13.	Ten - 6900 ft^3 ponds @$14000 (double supply)	$140,000	69,000ft^3
14.	Six starter, incubation ponds 8 × 80 × 2'3"	$ 36,000	1,440ft^3
15.	Two 1/2 acre asphalt ponds (74,700 ft^3 each)	$116,000	149,000ft^3
16.	Pond drains, 420' - 36", 6 valves	$ 18,620	
17.	Quard Piping 36" - 800', 24" - 240' + miscellaneous	$32,320	

18.	Access bridge (culvert?)	$ 25,000
19.	Service building (office, storage, shop, refrig.) 40 × 80	$ 72,000
20.	Rest rooms and facilities	$ 20,000
21.	Outside electric and overhead lights	$ 10,000
22.	Culverts	$ 2,430
23.	Guard rails	$ 1,440
24.	Equipment	$ 50,000
25.	Design	$ 60,000

Subtotal	
Contingencies	+ $ 58,000
Total	$1,124,270

$$\frac{\$1,124,270}{219,440\ ft^3} = \$5.123/ft^3$$

Table XI

Cost Estimate[13] for Salt Water Salmon Rearing Facility

	Expected Life[14]	Cost	One Hour Partial Replacement Cost
Husbandry pens (4 units, 50,000 ft^3 each)	2	$10,000	$5000
Shark pens	2	$ 5,000	$2500
Counter weights, concrete piles, anchors, etc.	2	$10,000	$5000
Pneumatic feeders	10	$ 5,000	$ 500
Amphibian truck (D.U.K.)	5	$ 2,500	$ 500
Float system (200 ft. @$.30/ft)	5	$ 5,000	$1000
Fish pump	5	$ 500	$ 100
			$14,600

$$\frac{\$14,600}{200,000\ ft^3} = \$0.073/ft^3$$

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[13] Ibid., Table 1.

[14] NMFS report suggests three year expected life while Domsea suggests two years for husbandry and shark pens.

Table XII

Operating, Maintenance and Feed Costs

Fall Chinook Group I

System	Item	Time Period	NMFS Mortalities Cost by System	NMFS Mortalities Cost by Year	State/NMFS Mortalities Cost by Year
Egg Incubation (100,000 eggs)	Utilities	1 Oct-2 Jan	47		
	Maintenance		12		
8.7% Mortality	Heated Water ($7.06/mo)		28	Year 1	Year 1
			$87	$85	$85
Pond Rearing (91,300 fry)	Feed (2089 lbs)	3 Jan-30 Apr	301		
	Medication		94		
14.9% Mortality	Utilities		57		
	Maintenance		94		
	Heated Water ($176/mo)		686	Year 2	Year 2
	Feed Storage ($11.76/mo)		57	2	2
			$1195	1195	1339
				6348	7292
				$7545	$8633
Pen Rearing and harvesting	Feed (64,587 lbs)	1 May-6 Apr	9559		
77,692 smolt	Medication		500		
+ 58,521 harvest	Utilities		166		
	Maintenance		101		
24.7% Mortality	D.U.K. operation		133		
	Miscellaneous materials		166		
	Feed storage (# 11.76/mo)		133	Year 3	Year 3
	Lease of land site ($11.76/mo)		133	5368	6167
	Lease of tidelands		?	212	212
	Undetermined (fish transportation, administrative, veterinary)		824	$5580	$6379
			$11715		
				Year 4	Year 4
				$218	$218
Brood Year 1	Feed = 74.50	$212			
4.5% Assummed	Other = 138.00				
Brood Year 2	Feed = 80.25	$218			
5% Assummed	Other = 138.00				

Note: "Other" includes labor for brood stock

Table XIII

Operating, Maintenance and Feed Costs

Fall Chinook Group II

System	Item	Time Period	Cost by System	NMFS Mortalities Cost by Year	State/NMFS Mortalities Cost by Year
Egg Incubation		24 Oct-25 Jan			
(100,000 eggs)	Utilities		47		
	Maintenance		12		
	Heated Water ($7.06/mo)		28	Year 1	Year 1
			$87	$63	$63
Pond Rearing		26 Jan-23 May			
(91,300 fry)	Feed (2089 lbs)		301		
	Medication		94		
	Utilities		57		
	Maintenance		94		
	Heated Water ($176/mo thru Apr)		552	Year 2	Year 2
	Feed Storage ($11.76/mo)		57	24	24
				1160	1315
				5196	5969
			$1160	$6380	$7308
Pen Rearing		24 May-30 Apr			
and Harvesting	Feed (64,587 lbs)		9559		
77,692 smolt	Medication		500		
58,521 harvest	Utilities		166		
	Maintenance		101	Year 3	Year 3
	D.U.K.		133	6519	7489
	Miscellaneous materials		166	200	200
	Feed Storage ($11.76/mo)		133	$6719	$7689
	Lease of land site ($11.76/mo)		133		
	Lease of tidelands		?		
	Undetermined(fish, transportation, administrative, veterinary)		825		
			$11715	Year 4	Year 4
Brood Year 1	Feed = 69, Other= 131 } $200			$248	$248
Brood Year 2	Feed = 85, Other = 163 } $248				

Table XIV

Operating, Maintenance and Feed Costs

Coho Group I

System	Item	Time Period	NMFS Mortalities Cost by System	NMFS Mortalities Cost by Year	State/NMFS Mortalities Cost by Year
Egg Incubation (100,000 eggs)		7 Nov-26 Jan			
	Utilities		47		
	Maintenance		12		
	Heated Water ($7.06/mo)		28	Year 1	Year 1
			$87	$58	$58
Pond Rearing (91,300 fry)		27 Jan-5 Aug			
	Feed(7740 lbs)		1116		
	Medication		94		
	Utilities		57	Year 2	Year 2
	Maintenance		94	29	29
	Heated Water ($176/mo, thru April)		528	1963	2122
	Feed Storage ($11.76/mo)		74	10807	11682
			$1963	6	6
				$12805	$13839
Pen Rearing and Harvesting		6 Aug-20 Nov			
	Feed (59,710 lbs)		8837		
	Medication		500		
	Utilities		166	Year 3	Year 3
	Maintenance		101	$246	$246
	D.U.K. Operation		133		
	Miscellaneous materials		166		
	Feed Storage ($11.76/mo)		40		
	Lease of land site ($11.76/mo)		40		
	Lease of tidelands		?		
	Undetermined (fish transportation, administrative, veterinary)		824		
			$10807	Year 4	Year 4
				$198	$198

Brood Year 0	Feed = 1.58	Other = 4.14	$6
Brood Year 1	Feed = 68	Other = 178	$246
Brood Year 2	Feed = 50	Other = 148	$198

Table XV

Operating, Maintenance and Feed Costs

Coho Group II

Systems	Item	Time Period	NMFS Mortalities: Cost by System	NMFS Mortalities: Cost by Year	State/NMFS Mortalities: Cost by Year
Egg Incubation (100,000 eggs)		1 Dec-17 Feb			
	Utilities		47		
	Maintenance		12	Year 1	Year 1
	Heated Water ($7.06/mo)		28	$34	$34
			$87		
Pond Rearing (91,300 fry)		18 Feb-28 Aug			
	Feed (7740 lbs)		1116		
	Medication		94	Year 2	Year 2
	Utilities		57	52	52
	Maintenance		94	1875	2027
	Heated Water ($176/mo thru April)		440	10807	11682
	Feed Storage ($11.76/mo)		74	3	3
			$1875	$12737	$13764
Pen Rearing and Harvesting		29 Aug-10 Dec			
	Feed (59,710 lbs)		8837		
	Medication		500	Year 3	Year 3
	Utilities		166	$243	$243
	Maintenance		101		
	D.U.K. Operation		133		
	Miscellaneous Materials		166		
	Feed Storage ($11.76/mo)		40		
	Lease of land site ($11.76/mo)		40		
	Lease of tidelands		?		
	Undetermined (fish transportation, administrative, veterinary)		824	Year 4	Year 4
			$10807	$203	$203

Brood Year 0	Feed = .80	Other = 2.18	$3
Brood Year 1	Feed = 65	Other = 177	$242
Brood Year 2	Feed = 54	Other = 149	$203

their salt water ration between May and December and the other half from January until they're harvested in April.

Feed costs for brood fish are currently very tenuous, this phase having never been actually accomplished. A commonly applied rule of thumb is that 25¢ worth of feed is required per pound of weight gained. Tables XVI, XVII and XVIII were derived using this method. Since the costs of rearing brood stock are quite small compared with those of rearing harvested fish it is felt that the solution would be insensitive to minor changes in this area.

Labor costs were scaled from the NMFS report, Appendix Table 3 and converted to costs incurred per year. Labor costs derived from a pilot project in general tend to be high (conservative) and it is suspected this is true here. In addition, by incubating eggs using the pond tray method as currently done by the State of Washington instead of the Heath incubator trays currently used, most of the part time labor costs associated with dead egg removal and most of the cost of incubators could be eliminated. Labor costs are summarized in Tables XIX, XX, XXI, and XXII for all four groups of fish considered.

Egg supply for those purchased in the first three years was based on a current Washington State Department of Fisheries price of $3.00 per 1000 eggs, including milt (sperm).

A summary of all operating and maintenance costs is included in Tables XXIII through XXIV. These tables form

			Coho #1	Coho #2
Start date / End date } # days			21 Nov / 31 Dec } 41	11 Dec / 31 Dec } 20
wt in of ____ fish			74.2÷2.0/lb =37.1 lbs	74.2÷2.0/lb =37.1 lbs
wt out of __ fish			73.4÷1.69/lb =43.4 lbs	73.4÷1.82/lb =40.3 lbs
Net wt gained			6.3 lbs	3.2 lbs
at 25¢/lb of wt gain = net food cost			$1.58	$.80

Table XVI

Feed Cost - Brood Year 0

	Fall Chinook #1	Fall Chinook #2	Coho #1	Coho #2
Start date / End date } # days	6 Apr / 31 Dec } 269	30 Apr / 31 Dec } 244	1 Jan / 31 Dec } 365	1 Jan / 31 Dec } 365
wt in of ____ fish	50.6÷2.0/lb = 25 lbs	50.6÷2.0/lb = 25 lbs	73.4÷1.69/lt = 43 lbs	73.2÷1.82/lb = 40 lbs
wt out of ____ fish	43.0÷.133/lb =323 lbs	43.0÷.142/lb =278 lbs	62.8÷.20/lb =271 lbs	62.8÷.21/lb =259 lbs
net wt gained	298 lbs	278 lbs	271 lbs	259 lbs
at 25¢/lb of fish = net food cost	$74.50	$69.50	$67.75	$64.75

Table XVII

Feed Costs - Brood Year 1

	Fall Chinook #1	Fall Chinook #2	Coho #1	Coho #2
Start date / End date } # days	1 Jan / 1 Oct } 304	1 Jan / 24 Oct } 327	1 Jan / 7 Nov } 311	1 Jan / 1 Dec } 335
wt in of ____ fish	43.0÷.133/lb =323 lbs	43.0÷.142/lb =303 lbs	62.8÷.20/lb =314 lbs	62.8÷.21/lb =299 lbs
wt out of ____ fish	32.2÷.05/lb =644 lbs	32.2÷.05/lb =644 lbs	61.6÷.10/lb =516 lbs	51.6÷.10/lb =516 lbs
net wt gained	321 lbs	341 lbs	202 lbs	217 lbs
at 25¢/lb of fish = net food cost	$80.25	$85.25	$50.50	$54.25

Table XVIII

Feed Costs - Brood Year 2

Month	System	Supervisor $15,000/Yr		Aide #1 $10,000/Yr		Aide #2 $10,000		Laborer #1 $9000/Yr		Laborer #2 $9000/Yr		Part time Labor -cost	Total cost	NMFS Mortalities		State/NMFS Mortalities	
		Days	Cost	Days	Cost	Days	Cost	Days	Cost	Days	Cost			Cost by system	Cost by year	Cost by system	Cost by year
Oct 1	Incubation	3.53	147.06	3.52	98.04	3.53	98.04					78.35	421.49				
Nov		3.53	147.06	3.53	98.04	3.53	98.04					78.35	421.49	1292.55	1264.47	1292.55	1264.47
Dec		3.53	147.06	3.53	98.04	3.53	98.04					78.35	421.49				
Jan 2		.24	9.80	.24	6.53	.24	6.53					5.22	28.08				
Jan 3	Pond Rearing	3.29	137.26	3.29	91.51	3.29	91.51					36.56	356.84				
Feb		3.53	147.06	3.53	98.04	3.53	98.04					39.18	382.32				
Mar		3.53	147.06	3.53	98.04	3.53	98.04					39.29	382.43	1504.02		1707.07	
Apr 30		3.53	147.06	3.53	98.04	3.53	98.04					39.29	382.43				
May 1	Pen Rearing	3.53	147.06	3.53	98.04	3.53	98.04	3.53	82.36	3.53	82.36		507.86				
Jun		3.53	147.06	3.53	98.04	3.53	98.04	3.53	82.36	3.53	82.36		507.86		5251.88		5882.95
Jul		3.53	147.06	3.53	98.04	3.53	98.04	3.53	82.36	3.53	82.36		507.86				
Aug		3.53	147.06	3.53	98.04	3.53	98.04	3.53	82.36	3.53	82.36		507.86				
Sept		3.53	147.06	3.53	98.04	3.53	98.04	3.53	82.36	3.53	82.36		507.86				
Oct		2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48	5001.75		5745.93	
Nov		2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48				
Dec		2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48				
Jan		2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48				
Feb		2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48		1281.97		1472.70
Mar		2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48				
Apr 6	Harvest	.71	29.41	.71	19.61	.71	19.61	.71	16.47	.71	16.47		101.57				

Table XIX

Labor Costs - Fall Chinook Group I

Month	System	Supervisor $15,000/Yr Days	Supervisor $15,000/Yr Cost	Aide #1 $10,000/Yr Days	Aide #1 $10,000/Yr Cost	Aide #2 $10,000/Yr Days	Aide #2 $10,000/Yr Cost	Laborer #1 $9000/Yr Days	Laborer #1 $9000/Yr Cost	Laborer #2 $9000/Yr Days	Laborer #2 $9000/Yr Cost	Part time Labor cost	Total cost	NMFS Mortalities Cost by system	NMFS Mortalities Cost by year	State/NMFS Mortalities Cost by system	State/NMFS Mortalities Cost by year
Oct 24	Incubation	.82	34.31	.82	22.88	.82	22.88					18.28	98.35				
Nov		3.53	147.06	3.53	98.04	3.53	98.04					78.35	421.49	1208.27	941.33	1208.27	941.33
Dec		3.53	147.06	3.53	98.04	3.53	98.04					78.35	421.49				
Jan 19		2.24	93.14	2.24	62.09	2.24	62.09					49.62	266.94				
Jan 20	Pond Rearing	1.29	53.92	1.29	35.95	1.29	35.95					14.37	140.18				
Feb		3.53	147.06	3.53	98.04	3.53	98.04					39.18	382.32				
Mar		3.53	147.06	3.53	98.04	3.53	98.04					39.29	382.43	1593.30		1806.34	
Apr		3.53	147.06	3.53	98.04	3.53	98.04					39.29	382.43				
May 24		2.82	117.65	2.82	78.43	2.82	78.43					31.43	305.94				
May 25	Pen Rearing	.71	29.41	.71	19.61	.71	19.61	.71	16.47	.71	16.47		101.57				
Jun		3.53	147.06	3.53	98.04	3.53	98.04	3.53	82.36	3.53	82.36		507.86		5173.69		5795.36
Jul		3.53	147.06	3.53	98.04	3.53	98.04	3.53	82.36	3.53	82.36		507.86				
Aug		3.53	147.06	3.53	98.04	3.53	98.04	3.53	82.36	3.53	82.36		507.86				
Sept		3.53	147.06	3.53	98.04	3.53	98.04	3.53	82.36	3.53	82.36		507.86				
Oct	(Egg Incubation, 2nd cycle)	2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48	4887.37		5614.53	
Nov		2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48				
Dec		2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48				
Jan		2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48				
Feb		2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48				
Mar		2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48				
Apr 30	Harvest	2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48		1639.83		1883.81

Table XX

Labor Costs - Fall Chinook Group II

Month	System	Supervisor $15,000/Yr Days	Supervisor $15,000/Yr Cost	Aide #1 $10,000/Yr Days	Aide #1 $10,000/Yr Cost	Aide #2 $10,000/Yr Days	Aide #2 $10,000/Yr Cost	Laborer #1 $9000/Yr Days	Laborer #1 $9000/Yr Cost	Laborer #2 $9000/Yr Days	Laborer #2 $9000/Yr Cost	Part time labor cost	Total cost	NMFS Mortalities Cost by System	NMFS Mortalities Cost by Year	State/NMFS Mortalities Cost by System	State/NMFS Mortalities Cost by Year
Nov 7	Incubation	2.82	117.65	2.82	78.43	2.82	78.43					62.68	337.19				
Dec		3.53	147.06	3.53	98.04	3.53	98.04					78.35	421.49	1123.97	758.68	1123.97	758.68
Jan 26		3.06	127.45	3.06	84.97	3.06	84.97					67.90	365.29				
Jan 27	Pond Rearing	.47	19.61	.47	13.07	.47	13.07					5.24	50.98				
Feb		3.53	147.06	3.53	98.04	3.53	98.04					39.18	382.43				
Mar		3.53	147.06	3.53	98.04	3.53	98.04					39.29	382.43				
Apr		3.53	147.06	3.53	98.04	3.53	98.04					39.29	482.43				
May		3.53	147.06	3.53	98.04	3.53	98.04					39.29	382.43	2508.53		2711.58	
Jun		3.53	147.06	3.53	98.04	3.53	98.04					39.29	382.43				
Jul		3.53	147.06	3.53	98.04	3.53	98.04					39.29	382.43				
Aug 5		.59	24.51	.59	14.84	.59	14.84					6.55	63.74				
Aug 6	Pen Rearing	2.94	122.55	2.94	81.70	2.94	81.70	2.94	68.63	2.94	68.63		432.21		4590.71		4962.34
Sept		3.53	147.06	3.53	98.04	3.53	98.04	3.53	82.36	3.53	82.36		507.86				
Oct		3.53	147.06	3.53	98.04	3.53	98.04	3.53	82.36	3.53	82.36		507.86	1710.25		1848.69	
Nov 20		1.69	65.36	1.69	43.57	1.69	43.57	2.35	54.91	2.35	54.91		262.32				

Table XXI

Labor Costs - Coho Group I

Month	System	Supervisor $15,000/Yr		Aid #1 $10,000/Yr		Aid #2 $10,000/Yr		Laborer #1 $9000/Yr		Laborer #2 $9000/Yr		Part time labor cost	Total Cost	NMFS Mortalities		State/NMFS Mortalities	
		Days	Cost	Days	Cost	Days	Cost	Days	Cost	Days	Cost			Cost by System	Cost by Year	Cost by System	Cost by Year
Dec	Incubation	3.53	147.06	3.53	98.04	3.53	98.04					78.35	421.49				
Jan		3.53	147.06	3.53	98.04	3.53	98.04					78.35	421.49	1081.82	421.49	1081.82	421.49
Feb 17		2.00	83.33	2.00	55.56	2.00	55.56					44.40	238.84				
Feb 18	Pond Rearing	1.53	63.72	1.53	42.48	1.53	42.48					17.03	165.90				
Mar		3.53	147.06	3.53	98.04	3.53	98.04					39.29	382.43				
Apr		3.53	147.06	3.53	98.04	3.53	98.04					39.29	382.43				
May		3.53	147.06	3.53	98.04	3.53	98.04					39.29	382.43	2460.48		2659.65	
Jun		3.53	147.06	3.53	98.04	3.53	98.04					39.29	382.43				
Jul		3.53	147.06	3.53	98.04	3.53	98.04					39.29	382.43				
Aug 28		3.29	137.26	3.29	91.50	3.29	91.50					39.29	382.43		4697.31		5077.56
Aug 29	Pen Rearing	.24	9.80	.24	6.54	.24	6.54	.24	5.49	.24	5.49		33.86				
Sept		3.53	147.06	3.53	98.04	3.53	98.04	3.53	82.36	3.53	82.36		507.86				
Oct		3.53	147.06	3.53	98.04	3.53	98.04	3.53	82.36	3.53	82.36		507.86	1573.62		1701.01	
Nov		2.35	98.04	2.35	65.36	2.35	65.36	3.53	82.36	3.53	82.36		393.48				
Dec 10	Harvest	.84	32.68	.84	21.79	.84	21.79	1.18	27.45	1.18	27.45		131.16				

Table XXII

Labor Costs - Coho Group II

Table XXIII

Cost Summary - State/NMFS Mortalities,

57¢/lb Return to Grower

Assume:

State hatchery system mortalities in fresh water

NMFS study mortalities in salt water

Harvest at 10.84 oz/fish

Cost of initial egg supply = \$300/100,000 eggs

Purchase fresh water site

Wholesale price = 57¢/lb to grower

Year i, i=1, 2, 3

Year		FC#1	FC#2	Coho#1	Coho#2
1	Eggs	300	300	300	300
	O+M	85	63	58	34
	Labor	1264	941	759	421
		1649	1304	1117	755
2	O+M	8633	7308	13833	13761
	Labor	5883	5795	4962	5078
	Receipts			-24422	-24422
		14516	13103	-5627	-5583
3	O+M	6167	7489		
	Labor	1473	1884		
	Receipts	-26189	-26189		
		-18549	-16816		
Net cost		-\$2384	-\$2409	-\$4510	-\$4828

Year i+3, i=1,...,7

Year		FC#1	FC#2	Coho#1	Coho#2
1					
2	Brood			6	3
3	Brood	212	200	246	243
4	Brood	218	248	198	203
	O+M	85	63	58	34
	Labor	1264	941	759	421
		1567	1252	1015	658
5	O+M	8633	7308	13833	13761
	Labor	5883	5795	4962	5078
	Receipts			-24422	-24422
		14516	13103	-5627	-5583
6	O+M	6167	7489		
	Labor	1473	1884		
	Receipts	-26184	-26189		
		-18544	-16816		
Net cost		-\$2249	-\$2261	-\$4360	-\$4679

Table XXIV

Cost Summary - NMFS Mortalities,

57¢/lb Return to Grower

Assume:

NMFS study mortalities

Harvest at 10.84 oz/fish

Cost of initial egg supply = $300/100,000 eggs

Purchase fresh water site

Wholesale price = 57¢/lb to grower

Year 1, 1 = 1, 2, 3

Year		FC#1	FC#2	Coho#1	Coho#2
1	Eggs	300	300	300	300
	O+M	85	63	58	34
	Labor	1264	941	759	421
		1649	1304	1117	755
2	O+M	7545	6380	12799	12734
	Labor	5252	5174	4591	4697
	Receipts			-22599	-22599
		12797	11554	-5290	-5168
3	O+M	5368	6514		
	Labor	1282	1640		
	Receipts	-22797	-22797		
		-16147	-14638		
Net cost		-$1701	-$1780	-$4173	-$4413

Year 1+3, 1 = 1,..., 7

Year		FC#1	FC#2	Coho#1	Coho#2
1					
2	Brood			6	3
3	Brood	212	200	246	243
4	Brood	218	248	198	203
	O+M	85	63	58	34
	Labor	1264	941	759	421
		1567	1252	1015	658
5	O+M	7545	6380	12799	12734
	Labor	5252	5174	4591	4697
	Receipts			-22599	-22599
		12797	11554	-5209	-5168
6	O+M	5368	6519		
	Labor	1282	1640		
	Receipts	-22797	-22797		
		-16147	-14638		
Net cost		-$1571	-$1632	-$3948	-$4264

the substance for cost entries in the formulation section of this paper. The model was tested for sensitivity to changes in price per pound to the grower. This involved only changing the "net" (objective function) and "receipts" portions of Tables XXIII through XXVI. These entries are shown in Tables C-I through C-III.

One fixed cost which occurs in the problem is the $100 per year license fee for salmon mariculture. Also, in the future a tidelands license fee may be levied by governmental agencies.

VI. MODEL FORMULATION

A. FRESH WATER SPACE REQUIREMENTS

Sufficient excess egg supply exists with the State of Washington hatchery system to guarantee egg availability for fall chinook on 1 October and 24 October. Similarly coho eggs would be available to a purchaser on 7 November and 1 December. Since the biological clock of salmon progeny is nearly identical to that of their forbearers,[15] it is reasonable to assume that a pattern of early and late fall chinook and coho could be maintained. Therefore it was decided to form four groups of fish for this problem. In doing so two purposes are served: the results are a little "smoother"; and the formulation becomes easier to modify as other species are added.

Fresh water volume is allocated to each of the four groups of fish in such a manner that no fresh water pond is ever loaded beyond a "safe limit" of two pounds of fish per cubic foot. Fall chinook group one is the first to hatch and be ponded, about 3 January. Since they reach 100 fish per pound and smolt about 30 April, the maximum required fresh water volume is allocated to group one when they are ponded. Between 26 January and 18 February,

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[15] "Manipulation of Columbia River Hatchery Coho Stocks to Meet the Needs of Fishery Management," Robert C. Hager, Washington State Department of Fisheries.

fall chinook group two and coho groups one and two enter fresh water at regular intervals. All the fish are constantly growing. On 30 April when fall chinook group one has smolted and is transported to salt water, it releases the pond space it was using in the hatchery. This makes 30 April the first critical date for loading the hatchery facilities. Optimally, all four groups should reach the maximum loading capacities for their respective pond allocations on 30 April. At this point, the three remaining groups in the hatchery are "split out" so that at the next critical date, 23 May, when fall chinook group two departs for salt water, coho groups one and two can be "split out" into the now available space. After coho group one departs, the entire hatchery is available for group two coho.

For scaling purposes, 100,000 eggs are started. Space is allocated to surviving fish as described in Chapter IV of this paper. The resulting matrix entries and formulation are shown in Table IX.

B. FRESH WATER SPACE ALLOCATION

Fresh water pond facilities are intrinsically of a permanent nature, being commonly built of concrete or asphalt. Therefore, ponds built in any year remain available for all succeeding years. To maintain continuity of units, ponds built in year i are in units of cubic feet.

The composite fresh water section thus becomes one of cubic feet of ponds required in year i per number of fish

of group j, summed over all four groups minus the total number of ponds built up thru year i. Pond space required minus that available for each row must thus be less than or equal to zero.

In the fall of year 1 pond space is allocated for incubation. This space is already in existance in ensuing years because of normal hatchery expansion and would not be in use except for incubation. Ensuing ponds must be built in year i+1 for use by fish incubated in year i.

C. SALT WATER SPACE REQUIREMENTS

The "critical dates" in salt water are computed much the same as in fresh water, except loading densities are maintained no greater than 1 1/2 pounds of fish per cubic foot up through harvest.

At harvest .0005 of the number of progeny coho to be started are removed to adult brood pens and their ensuing space requirement charged against year i+3 in which the progeny will be harvested. This is based on an expected fecundity of 2903 for coho. Fall chinook fecundity is about 4652 and therefore only .00002 of those harvested are retained for brood. One male is removed for every two females. The number of fish retained for brood stock are thus too small for the model to be sensitive to them and are thus not discounted from the harvest.

Harvest dates for coho are about 20 November and 10 December, when the fish reach a weight of about 11 ounces each. Fall chinook grow slower and are harvested about

6 April and 30 April. The matrix entries are shown in Table IX, based again on cubic feet per 100,000 eggs started minus total expected mortalities up through critical date in question.

D. SALT WATER SPACE ALLOCATIONS

Pens currently in use for salt water salmon rearing are constructed of nylon webbing. The life expectancy is two years, so pens built in year i-1 and year i are available in year i. Pens are constructed in units of cubic feet.

The salt water facilities section consists of the sum of all salt water requirements at critical points Y(year) P(period) each multiplied by the numbers of fish in 100,000 units, minus the facilities available. This sum must be less than or equal to zero for each period. This results in at least as much space being available as is required.

E. COSTS

The cost section is formulated in two sections, the first being operating, maintenance and revenue and the second being construction costs.

Costs incurred by each group of fish are separated by year. The expected revenue based on survival and price to the grower is subtracted from the operating and maintenance costs in the year of the particular harvest. In this way

revenue is not realized on a group of fish during its initial growth phase.

Costs associated with brood stock is charged against the progeny that will be harvested.

Construction costs are calculated in dollars per cubic foot. This is computed by dividing the composite cost of a hatchery or salt water facility by its total capacity.

In year one a portion of the available capital is used. Excess is held for use in ensuing years by a system of slack variables, so the initial sum is optimally spread over as much of the problem as necessary before a profit is realized.

F. OBJECTIVE FUNCTION

The objective function is written in terms of maximizing net profit. The gross profit minus operating and maintenance costs for each group of fish are multiplied by the number to start (in units of 100,000 eggs) and summed over all groups. From this is subtracted the total cost of cubic feet of ponds and pens to be constructed in year i, leaving net profit. Slack variables are multiplied by zero in the objective function as are net revenues for year ten fish and groups one and two of year nine fish. This is discussed under subsection H. Costs and revenues were not discounted by year. This is left for future investigators.

G. BOUNDS

Lower bounds are placed on the problem so negative ponds and pens can't be constructed.

H. ENDPOINTS

Terminating a dynamic linear programming formulation such as this can be cumbersome. Fish started in year 10 aren't harvested until years 11 and 12. Unless a cut off point is predetermined, the problem becomes unbounded. This is obviously undesirable and results past the sixth or seventh year are useless anyhow. Changing technology alone would make very long term planning in detail unrealistic.

To terminate the problem at the end of the 10th year the author built a 10 year matrix with all entries included as if the problem would continue indefinitely. This retained symmetry in the basic matrix. Since fish started in year ten and types one and two fish started in year nine (fall chinook) would not be harvested until after year ten, the net profit for these fish, in the objective function was set at zero.

This attack allowed the facility to grow in a very realistic pattern, as shown in the results section of this paper.

I. SUMMARY

In brief, the model was formulated as

$$\text{Max} \sum_{i=1}^{9} \sum_{\substack{j=1 \\ i<10}}^{4} a_{ij} w_{ij} - \sum_{i=1}^{10} bx_i - \sum_{i=2}^{10} cu_i + \sum_{i=1}^{10} 0 \cdot s_i$$

$$\text{ST:} \quad \sum_{j=1}^{4} h_{1jp_f} \cdot w_{ij} - 1 \cdot x_1 \leq 0$$

$$\sum_{j=1}^{4} d_{(i+1)jp_f} \cdot w_{ij} - \sum_{L=1}^{10} 1 \cdot x_L \leq 0 \quad p = 1,\ldots,7$$

$$\sum_{k=1}^{9} \sum_{j=1}^{4} e_{(i+1)jp_k} \cdot w_{ij} - \sum_{\substack{L=i-1 \\ L\geq 3}}^{i} 1 \cdot u_L$$

$$\leq 0: \; p_s = 1,\ldots,13$$

$$i = 3,\ldots,10$$

$$\sum_{j=1}^{4} f_{ijk} \cdot w_{ij} - bx_i - cu_i + S_i = M \quad \text{if } i = 1$$

$$\sum_{k=2}^{10} \sum_{j=1}^{4} f_{ijk} \cdot w_{ij} - bx_i - cu_i - S_{i-1} + S_i = 0$$

$$\text{if} \quad i>1$$

$$w_{ij} \geq 0, \quad i=1,\ldots,9; \; j=1,\ldots,4 (i\neq 9); \; j=3,4 (i=9)$$

$$x_i \geq 0, \quad i=1,\ldots,10$$

$$u_i \geq 0, \quad i=2,\ldots,10$$

$$S_i \geq 0, \quad i=1,\ldots,10$$

where i = current year

j = type of salmon; here type 1 = fall chinook (early)

type 2 = fall chonook (late)

type 3 = coho (early)

type 4 = coho (late)

p_f = critical date, fresh water phase

p_s = critical date, salt water phase

k = year in which the type of salmon were started

a_{ij} = net revenue for salmon of type j that were started in year i. (Gross revenue at harvest - operating, feed and maintenance costs)

w_{ij} = numbers of eggs of fish type j to be started in year i in units of 100,000 eggs

b = cost of constructing one cubic foot of hatchery space, including all piping, yarding, etc.

x_L = number of cubic feet of hatchery space to construct in year i

c = cost of constructing one cubic foot of salt water pen space, including secondary costs of floats, etc.

u_i = number of cubic feet of pen space to construct in year i

s_i = slack variable in year i

d_{ijp_f} = cubic feet of fresh water hatchery space required by fish of type j in year i in period p_f

e_{ijp_s} = cubic feet of salt water space required by fish of type j in year i in period p_f

f_{ijb} = net operating, feed and maintenance cost minus revenue received if in a harvest year for fish of type j started in year i

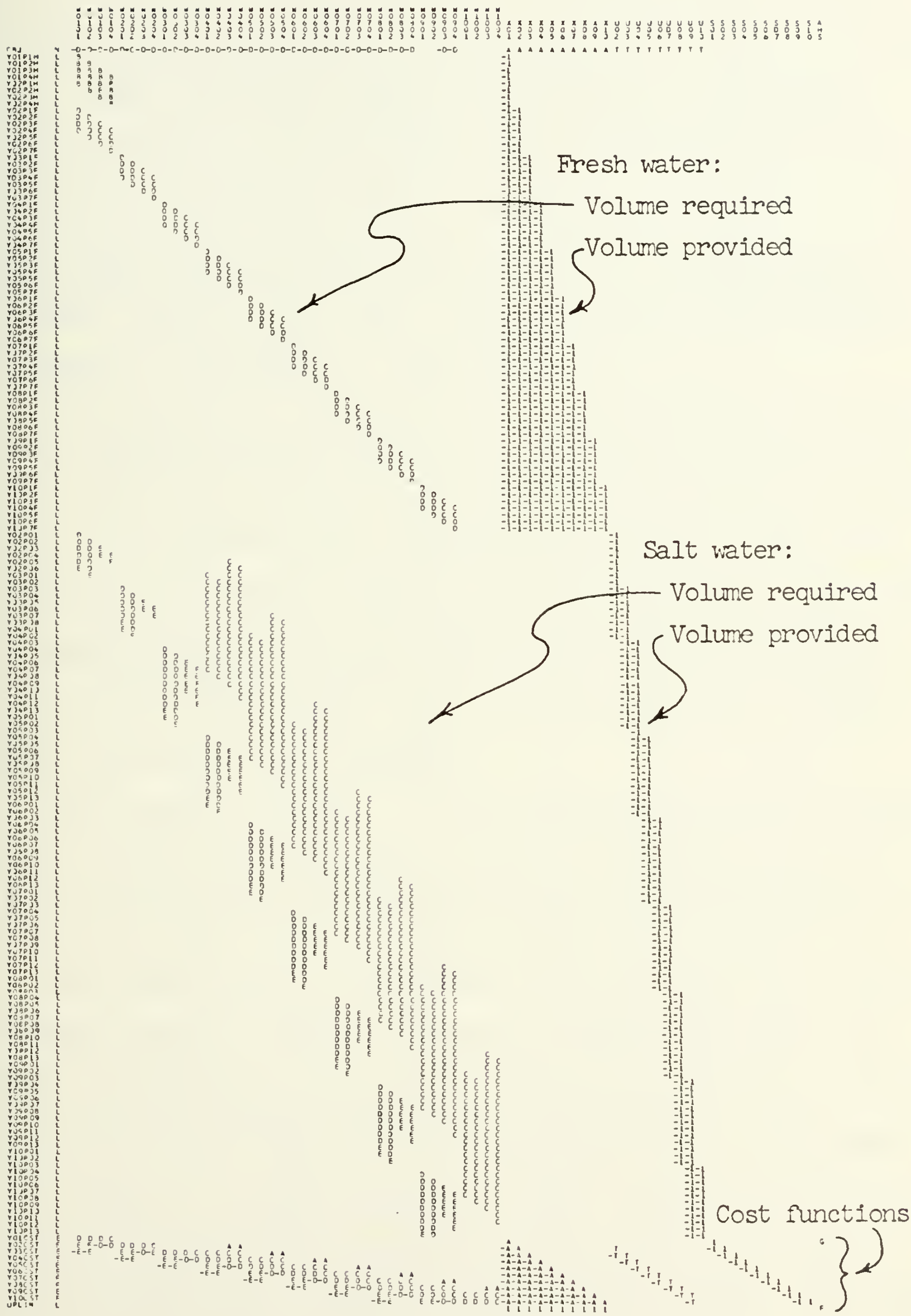
M = money available at start of program

h_{ijp_f} = cubic feet of fresh water hatchery space required to incubate eggs of type j in year i in period p_f

Table XXV shows a complete formulation of the linear programming matrix.

Table XXV

Complete Matrix Formulation



VII. SUMMARY

The model was solved on the IBM 360/67 computer at the W.R. Church Computer Center at the Naval Postgraduate School, Monterey, California, using IBM's "Mathematical Program System/360, Version 2, Linear and Separable Programming, Program Number 360A-CO-14X." "Picture" and "range" options were used. Parameters used were XTOLDJ=.01, XTOLERR=.1, XTOLCHK=.01, and XEPS=.01.

Solutions were achieved for a steady state system and for a system that was allowed to grow to a maximum allowable size. By ensuring that the cumulative pond, space constructed in years one through ten was less than the volume of Humptulips hatchery and the total funds required to build the hatchery were available in year one, steady state solutions were achieved.

The growth solution was calculated with the assumption of $300,000 available in year one and allowing the fresh water facility to grow to the size of Humptulips.

The above cases were solved for both Liao and Bergman loading factors and for mortality predictions from the NMFS and Washington State data mentioned earlier. Break even points (no revenue) were arrived at for the steady state system through trial and error. Objective function (profit) figures were calculated for 57¢/lb and 60¢/lb in all eight cases and are shown in Table XXVI. Also shown

System Growth Formulations

Loading Mortalities / Price/lb	Bergman NMFS	Bergman State/NMFS	Liao NMFS	Liao State/NMFS	
60¢	$4,196,493 3 Years	$4,787,198 3 Years	$11,530,322 3 Years	$12,147,741 3 Years	Objective function # Years of growth
57¢	$2,123,395 3 Years	$2,585,652 3 Years	$6,567,172 2 Years	$6,701,777 4 Years	Objective function # Years of growth

Steady State Formulations

60¢	$4,610,987	$5,532,798	$12,757,955	$14,340,418	Objective function
57¢	$2,507,209	$3,051,003	$6,244,576	$7,604,198	Objective function
55¢	$ 820,516	/ / / / /	/ / / / /	/ / / / /	Objective function
54¢	$ 0	$ 629,870	$ 912,106	$1,946,024	Objective function
53¢	/ / / / /	$ 0	$ 0	$ 0	Objective function

Break even points for positive revenues

Table XXVI. Objective Function Values (Revenues Realized)

in the growth tabulation is the number of years that ponds continue to be constructed until the system reaches the full size of one hatchery.

Table XXVII shows the optimal steady state fish rearing pattern for each of the four steady state formulations. The objective function values shown are relative and in fact show only a relative ranking of profitability. The objectives function values are, however, fairly close to those actually achievable.

The initial objective of this thesis, however, was to show the growth pattern for construction of facilities and patterns for rearing the various types of fish. Table XXVIII shows the patterns for constructing ponds and pens for each of the four system growth problems. Table XXIX shows the optimal construction pattern for a steady state operation.

A sensitivity analysis was completed for each of the following sixteen cases: Bergman and Liao loading schemes State/NMFS and NMFS mortalities, growth and steady state and 57¢ and 60¢/lb return to grower. All cases other than the four Bergman loading and State/NMFS mortalities cases proved to be quite insensitive to errors in costs and revenues. For fish of group j started in year i, in less than 15% of the groups would the optimal operation play be changed by a marginal decrease in revenues. This figure was 42% in the other four cases.

Table XXVII

Numbers of Eggs to be Started in Each Year

in Steady State Operation

Loading Mortalities	Bergman State/NMFS	Bergman NMFS	Liao State/NMFS	Liao NMFS
Group				
Fall Chinook #1	3,850,000	3,810,000	22,270,000	19,600,000
Fall Chinook #2	7,170,000	7,090,000	29,860,000	26,150,000
Coho #1	2,400,000	2,250,000	3,840,000	3,480,000
Coho #2	7,560,000	6,900,000	12,880,000	11,910,000

Table XXVIII

Optional Facilities Construction Patterns at 57¢/lb to Grower (Facility allowed to Grow)

Pond Construction (Ft^3)

Loading Mortalities	Bergman NMFS	Bergman State/NMFS	Liao NMFS	Liao State/NMFS
Year				
1	50,679	51,289	20,200	46,623
2	54,397	54,140	199,239	57,359
3	114,365	114,011	0	104,964
4	0	0	0	10,495
5-10	0	0	0	0

Pen Construction (Ft^3)

1	0	0	0	0
2	938,320	935,683	3,515,135	1,536,371
3	1,590,451	1,095,836	4,192,476	1,709,346
4	767,518	1,274,134	4,215,040	4,938,516
5	2,025,684	1,562,728	3,527,076	3,498,622
6	329,289	807,226	4,880,820	4,938,516
7	2,025,611	2,024,218	3,512,761	3,487,763
8	297,374	315,499	4,598,969	4,631,791
9	1,958,723	1,946,648	3,416,932	3,417,055
10	0	0	0	0

Table XXIX

Optimal Facilities Construction Patterns at 57¢/lb to Grower. (Facility Started Fully Capitalized, Steady State)

Pond Construction (Ft^3)

Loading Mortalities	Bergman NMFS	Bergman State/NMFS	Liao NMFS	Liao State/NMFS
Year				
1	186,327	189,015	178,110	180,675
2	33,112	30,425	41,330	38,765
3	0	0	0	0
4-10	0	0	0	0

Pen Construction (Ft^3)

1	0	0	0	0
2	2,093,973	2,086,298	3,373,486	3,365,512
3	677,742	725,363	683,872	718,949
4	1,680,215	1,644,607	4,354,075	6,322,601
5	1,113,661	1,192,263	3,362,703	3,322,637
6	1,244,295	1,177,710	5,038,204	5,114,501
7	1,549,581	1,658,909	3,354,930	3,311,258
8	776,680	682,841	4,755,778	4,807,464
9	1,958,723	1,946,648	3,260,124	3,241,384
10	0	0	0	0

The author was intrigued by the results showing that fall chinook were to be reared when coho were much more profitable. For comparison, one solution was computed with fall chinook started set to zero. The patterns of rearing coho in each case is shown in Table XXX for NMFS mortalities, steady state, 60¢/lb. The marginal increase of 60,775 coho that can be started is far outbalanced by the 6,015,944 fall chinook that are sacrificed. The fall chinook are quite small when the coho are harvested, so the profit realizable from allocating space to fall chinook and thereby using what would otherwise be wasted facility is greater than the profit if the entire facility were given to coho. Interestingly, when fall chinook were omitted from the 57¢/lb Bergman loading plans, insufficient revenue was realized to warrent starting the facility.

Table XXX

Number of Coho Started

With Fall Chinook		Without Fall Chinook	
Coho #1	Coho #2	Coho #1	Coho #2
2,399,713	7,560,560	2,541,829	7,397,669

VIII. CONCLUSIONS

The study illustrates that the profit realized is much more sensitive to the hatchery loading scheme than price per pound to the grower. The Liao loading formulae resulted in nearly three times the revenue over a ten year period than the Bergman method. Only a twelve percent increase in revenues resulted from the difference in expected mortalities. These results are reflected in Table XXVI.

As expected, the total numbers of fish to start in any year decreases with decreased mortalities, as shown in Table XXVII. A somewhat surprising result of this table, is the large number of fall chinook to start in each year. These values may be high due to possibly conservative cost and mortality figures assigned to the fall chinook. Improved data should resolve this apparent disparity.

Pen construction follows a cycle of alternate highs and lows as shown in Table XXVIII and XXIX. These are caused by the two year life expectancy of pens. Lower than expected pen construction in years 8, 9 and 10 illustrate end point problems and these data should not be used.

The problem was solved on the computer with $300,000 starting capital and allowed to grow without bound for ten years. This approach resulted in rearing only coho. The

result was unrealistic in that all fish were being reared to capitalize on the last two years where not all costs can be accounted for due to end point limitations as discussed earlier.

An interesting area for further study would be to determine the optimal amount of investment capital to put into such an operation. Given an assummed maximum facility size, a sequence of initial capitalizations would yield various objective function values (revenues). From these revenues should be subtracted the opportunity cost of the initial capitalization. Too little capitalization would result in too small a revenue while too large a capitalization would yield a high opportunity cost for the initial funds, and again a low profit. This attack would be warranted with more well-defined initial data.

In conclusion, when a firm considers an operation such as this, there are many points to be seriously considered. The system is quite sensitive to price to the grower, with revenues nearly doubling for every three cent per pound increase in price per pound to the grower. Expected mortalities also bear heavily on the outcome. As stated earlier in the thesis, the outcomes shown are valid for the sets of assumptions made. Some of the assumptions may not be compatible as used. For instance, Liao's loading scheme may cause mortalities to be much higher than assummed for this paper. Many of these contingencies are based on little or no data in the salt

water phase and therefore must be proven before much confidence can be given to at least the more optimistic results of this paper.

In addition, risks due to disease, floods, log booms breaking up near salt water pens, and marine growth make the risk involved in such an operation extremely high. One natural disaster could wipe out an entire year's stocks and even seriously damage the facilities. The high risk and large cost of initial facilities would probably reduce competition except from extremely well-backed firms, however. Prices would probably be fairly secure from competition at least over the next five years.

In summary, if a firm is willing to assume the risks, an operation of this type is not only feasible, but holds the potential for high profits.

Table A-I

Fecundity

Species	# Females	Number of eggs per female	
		Mean	Standard deviation
Fall Chinook	41,160	4652	532.8
Coho	38,147	2903	363.9

Table A-II

Fresh Water Temperature as a Function of Age of Fish

Weeks Reared	Average Temperature	
	Fall Chinook	Coho
1	42.6	47.4
2	42.9	48.0
3	42.9	49.7
4	44.0	50.8
5	43.9	52.3
6	44.3	52.6
7	45.4	53.7
8	45.8	54.8
9	46.1	54.8
10	47.1	55.0
11	47.9	55.8
12	49.8	55.9
13	49.6	56.1
14	50.9	56.6
15	51.7	56.7
16	52.4	56.5
17	52.2	56.6
18	51.7	56.3
19		56.4
20		56.1
21		56.0
22		55.9
23		55.7
24		55.2
25		55.7
26		54.9
27		54.5
28		54.5

Table B-I

Statistical Information for Plot of Fall Chinook: Days Reared versus Ln (# Fish per Pound) and Days Reared versus # Fish per Pound, Fresh Water

REMAINING SAMPLE SIZE= 549

SUMS

3324.0107	25344.0000	292501.0000

MEANS

6.0547	46.1639	532.7886

CROSS PRODUCT DEVIATIONS

	COL. 1	COL. 2	COL. 3
1	302.1851	-11177.0156	116515.1875
2	-11177.0156	450958.6875	-4522528.0000
3	116515.1875	-4522528.0000	50030864.0000

STANDARD DEVIATIONS

0.7426	28.6865	302.1543

VARIANCE-COVARIANCE MATRIX

	COL. 1	COL. 2	COL. 3
1	0.5514	-20.3960	212.6189
2	-20.3960	822.9172	-8252.7852
3	212.6189	-8252.7852	91297.1875

CORRELATION MATRIX

	COL. 1	COL. 2	COL. 3
1	1.0000	-0.9575	0.9476
2	-0.9575	1.0000	-0.9521
3	0.9476	-0.9521	1.0000

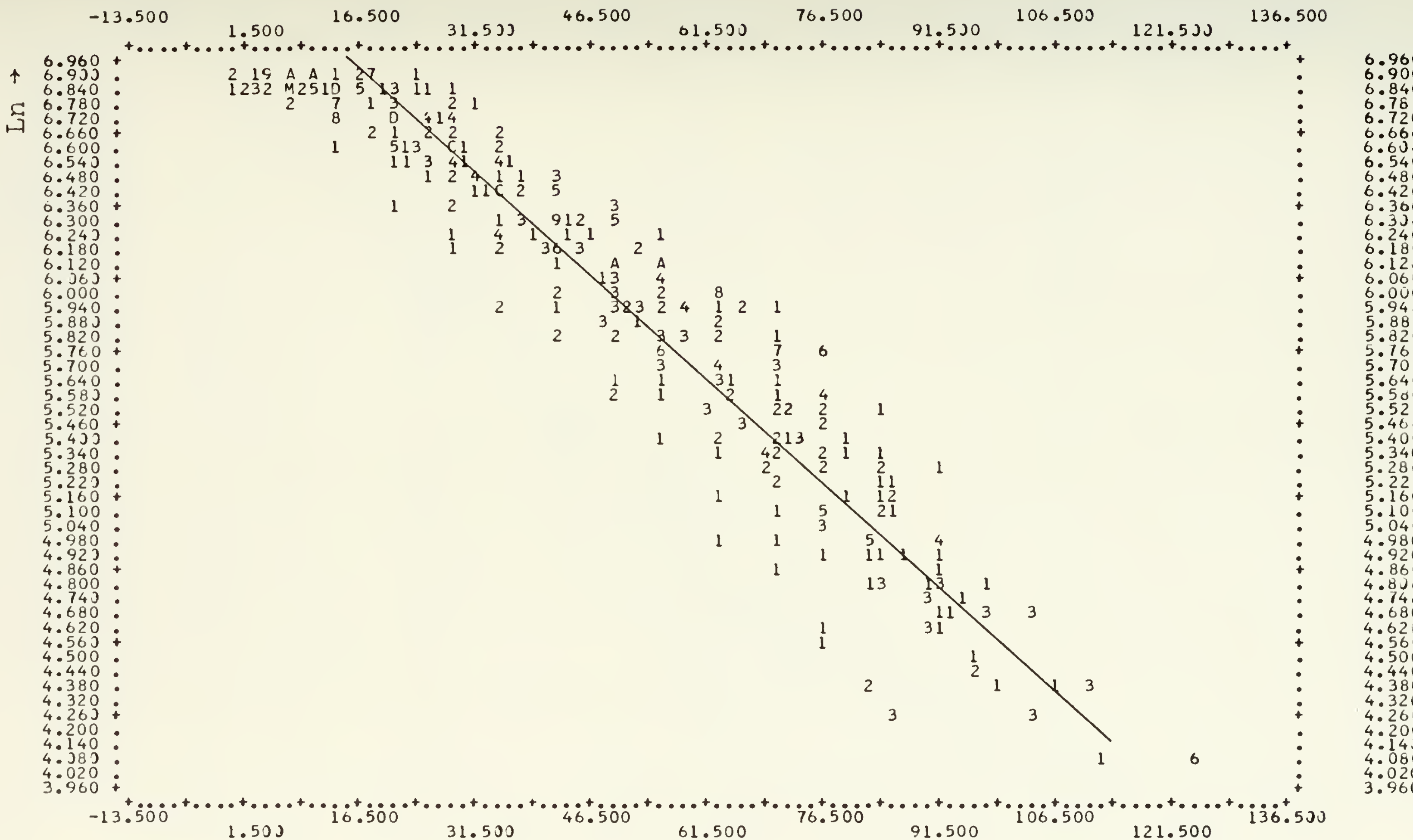


Table B-II

Scatter Diagram and Regression Line for

Fall Chinook: Days Reared versus Ln (# Fish per Pound), Fresh Water

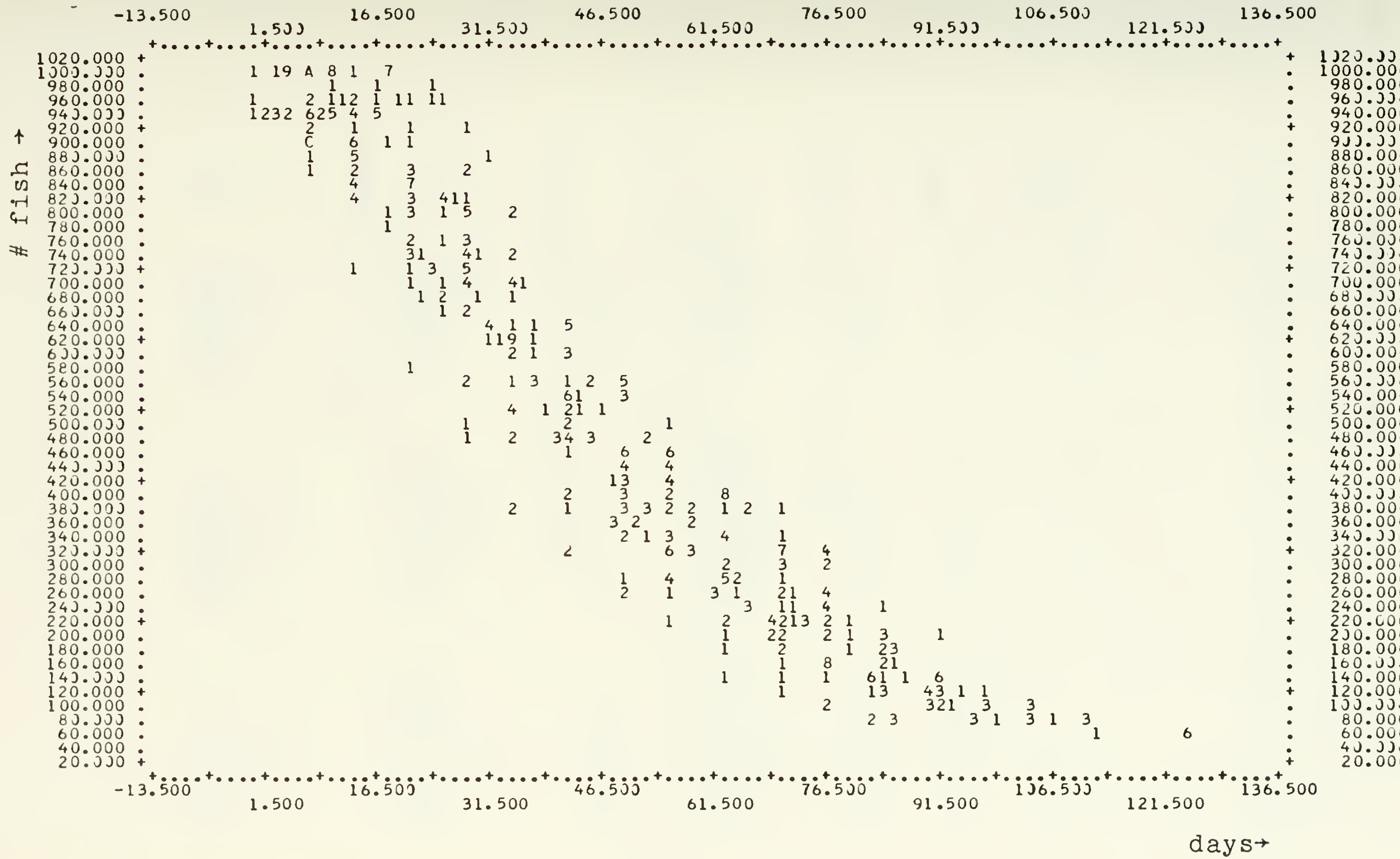


Table B-III

Scatter Diagram for Fall Chinook: Days Reared versus # Fish per Pound, Fresh Water

Table B-IV

Statistical Information for Plot of Fall Chinook: Days Reared (Beyond First 20 Days) versus Ln (# Fish per Pound) and Days Reared (Beyond First 20 Days) versus # Fish per Pound, Fresh Water

REMAINING SAMPLE SIZE= 428

SUMS

2496.0200	24098.0000	178836.0000

MEANS

5.8318	56.3037	417.8411

CROSS PRODUCT DEVIATIONS

	COL. 1	COL. 2	COL. 3
1	205.2439	-6776.3359	66296.5000
2	-6776.3359	248341.7500	-2247178.0000
3	66296.5000	-2247178.0000	23936224.0000

STANDARD DEVIATIONS

0.6933	24.1163	236.7630

VARIANCE-COVARIANCE MATRIX

	COL. 1	COL. 2	COL. 3
1	0.4807	-15.8696	155.2611
2	-15.8696	581.5964	-5262.7109
3	155.2611	-5262.7109	56056.7305

CORRELATION MATRIX

	COL. 1	COL. 2	COL. 3
1	1.0000	-0.9492	0.9459
2	-0.9492	1.0000	-0.9217
3	0.9459	-0.9217	1.0000

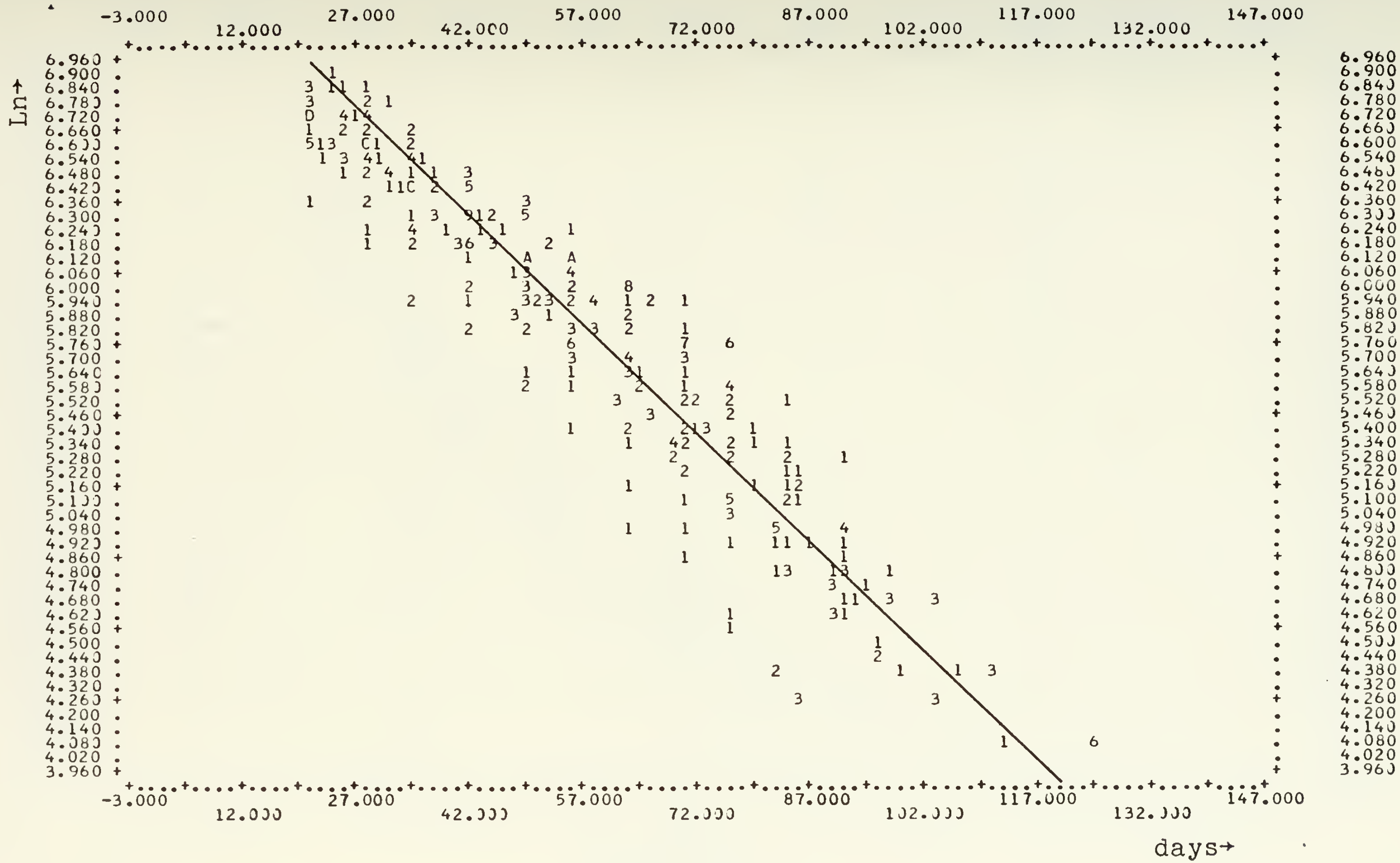


Table B-V

Scatter Diagram and Regression Line for Fall Chinook: Days Reared (Beyond First 20 Days) versus Ln (# Fish per Pound), Fresh Water

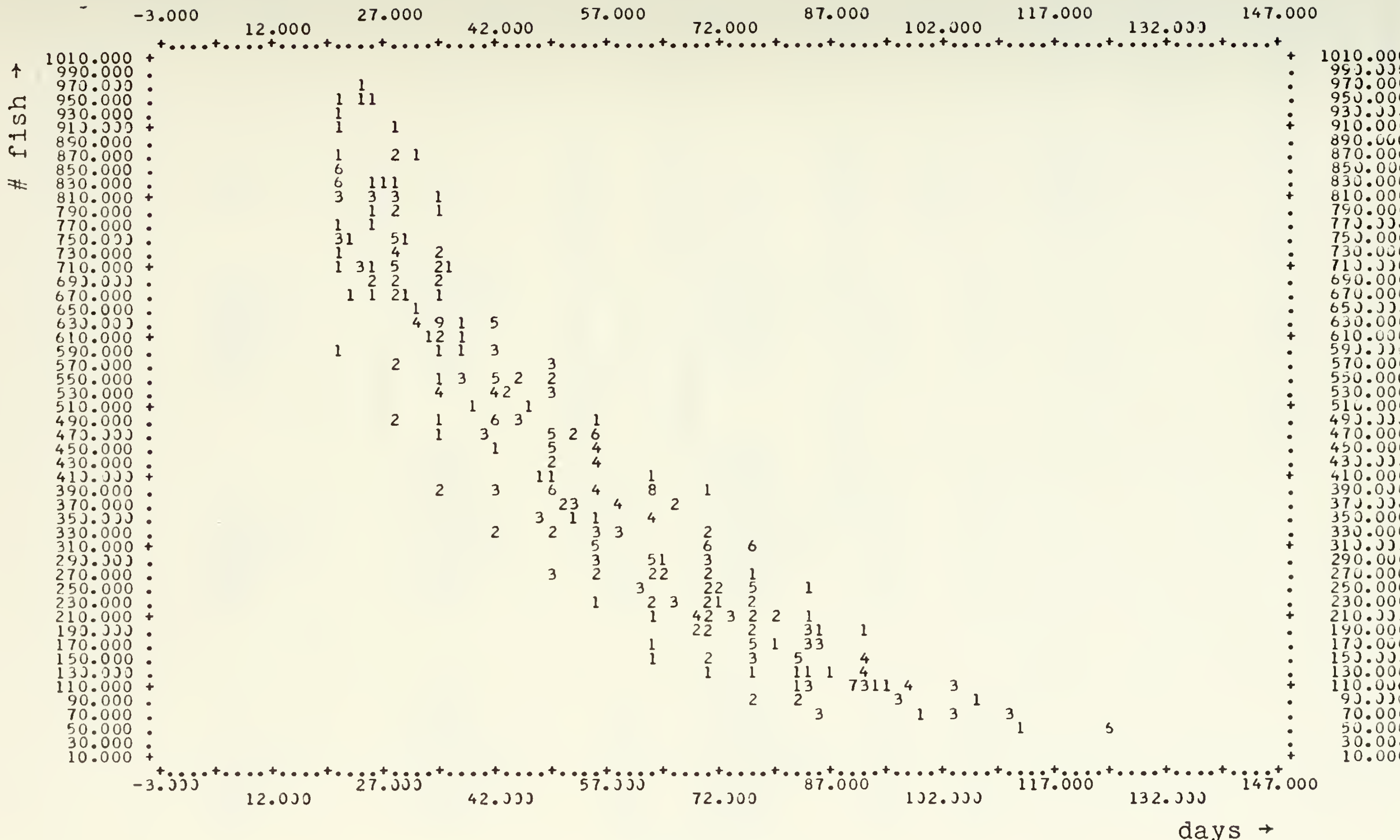


Table B-VI

Scatter Diagram for Fall chinook: Days Reared (Beyond First 20 Days) versus # Fish per Pound, Fresh Water

Table B-VII

Statistical Information for Plot of Fall Chinook: Days Reared versus Ln (# Fish per Pound) and Days Reared versus # Fish per Pound, Salt Water

REMAINING SAMPLE SIZE= 12

SUMS

23.9299	3353.0000	164.9024

MEANS

1.9942	279.4165	13.7419

CROSS PRODUCT DEVIATIONS

	COL. 1	COL. 2	COL. 3
1	13.3212	-1214.0681	203.4155
2	-1214.0681	119212.8750	-16790.0039
3	203.4155	-16790.0039	3689.2083

STANDARD DEVIATIONS

1.1005	104.1035	18.3134

VARIANCE-COVARIANCE MATRIX

	COL. 1	COL. 2	COL. 3
1	1.2110	-110.3698	18.4923
2	-110.3698	10837.5313	-1526.3638
3	18.4923	-1526.3638	335.3826

CORRELATION MATRIX

	COL. 1	COL. 2	COL. 3
1	1.0000	-0.9634	0.9176
2	-0.9634	1.0000	-0.8006
3	0.9176	-0.8006	1.0000

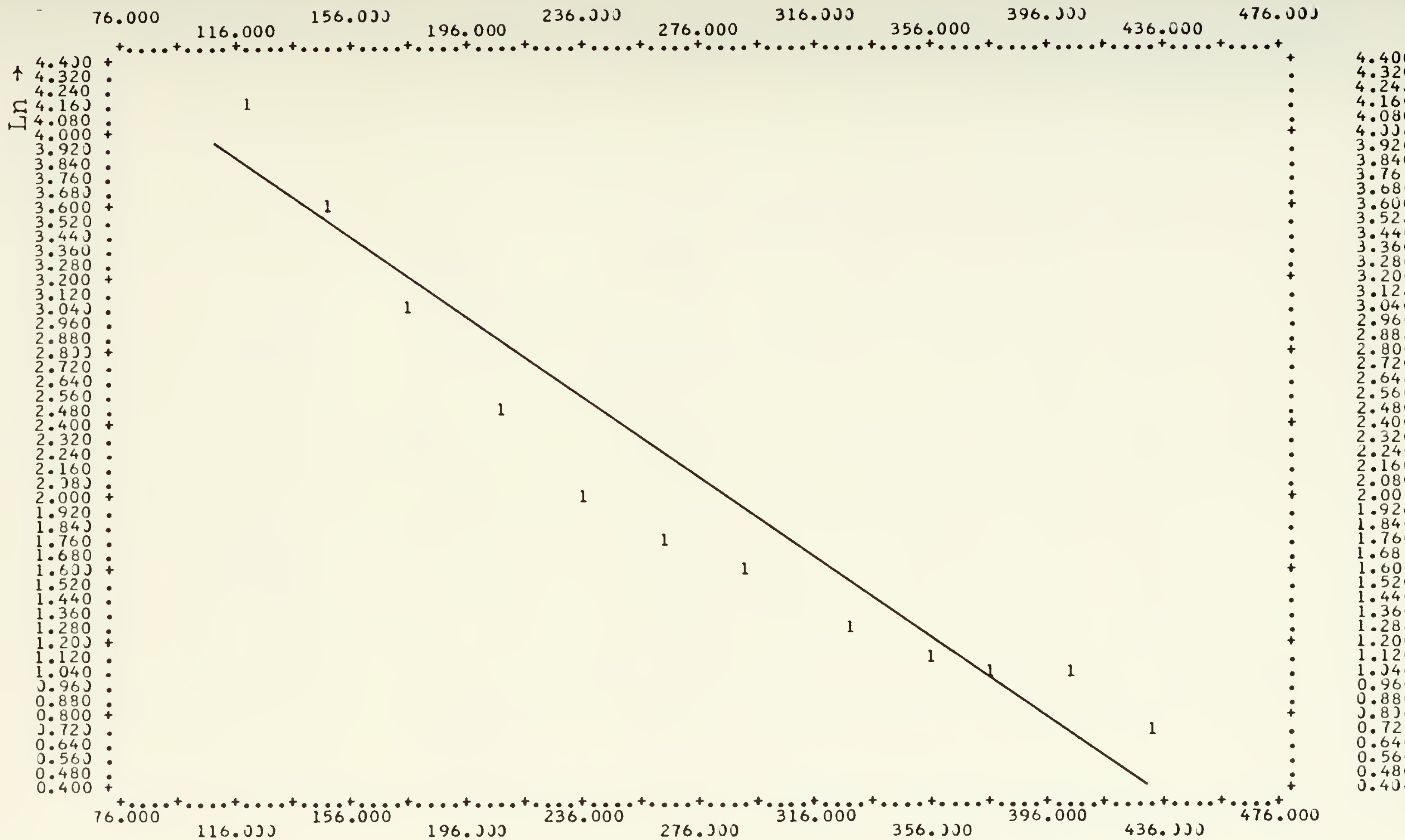


Table B-VIII

Scatter Diagram and Regression Line for Fall Chinook: Days Reared versus Ln (# Fish per Pound), Salt Water

Table B-IX

Scatter Diagram for Fall Chinook: Days Reared versus

Fish per Pound, Salt Water

Table B-X

Statistical Information for Plot of Coho: Days Reared versus Ln (# Fish per Pound) and Days Reared versus # Fish per Pound, Fresh Water

REMAINING SAMPLE SIZE= 268

SUMS

1353.7998	30122.0000	78789.0000

MEANS

5.0515	112.3955	293.9888

CROSS PRODUCT DEVIATIONS

	COL. 1	COL. 2	COL. 3
1	300.9583	-14676.0313	98010.5000
2	-14676.0313	728539.8750	-4714701.0000
3	98010.5000	-4714701.0000	37827664.0000

STANDARD DEVIATIONS

1.0617	52.2361	376.3997

VARIANCE-COVARIANCE MATRIX

	COL. 1	COL. 2	COL. 3
1	1.1272	-54.9664	367.0803
2	-54.9664	2728.6135	-17658.0547
3	367.0803	-17658.0547	141676.6250

CORRELATION MATRIX

	COL. 1	COL. 2	COL. 3
1	1.0000	-0.9911	0.9186
2	-0.9911	1.0000	-0.8981
3	0.9186	-0.8981	1.0000

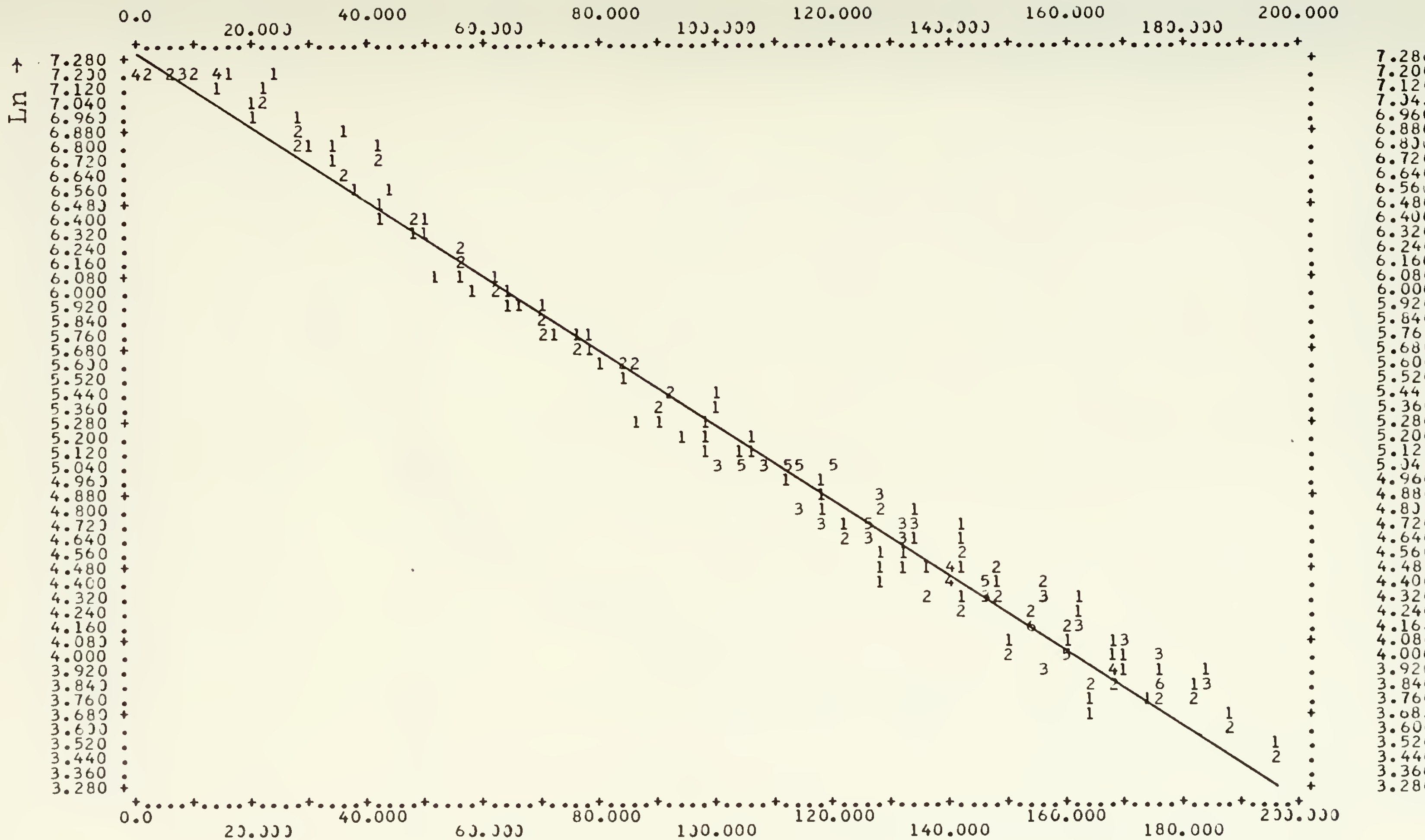


Table B-XI

Scatter Diagram and Regression Line for Coho: Days Reared versus Ln (# Fish per Pound), Fresh Water

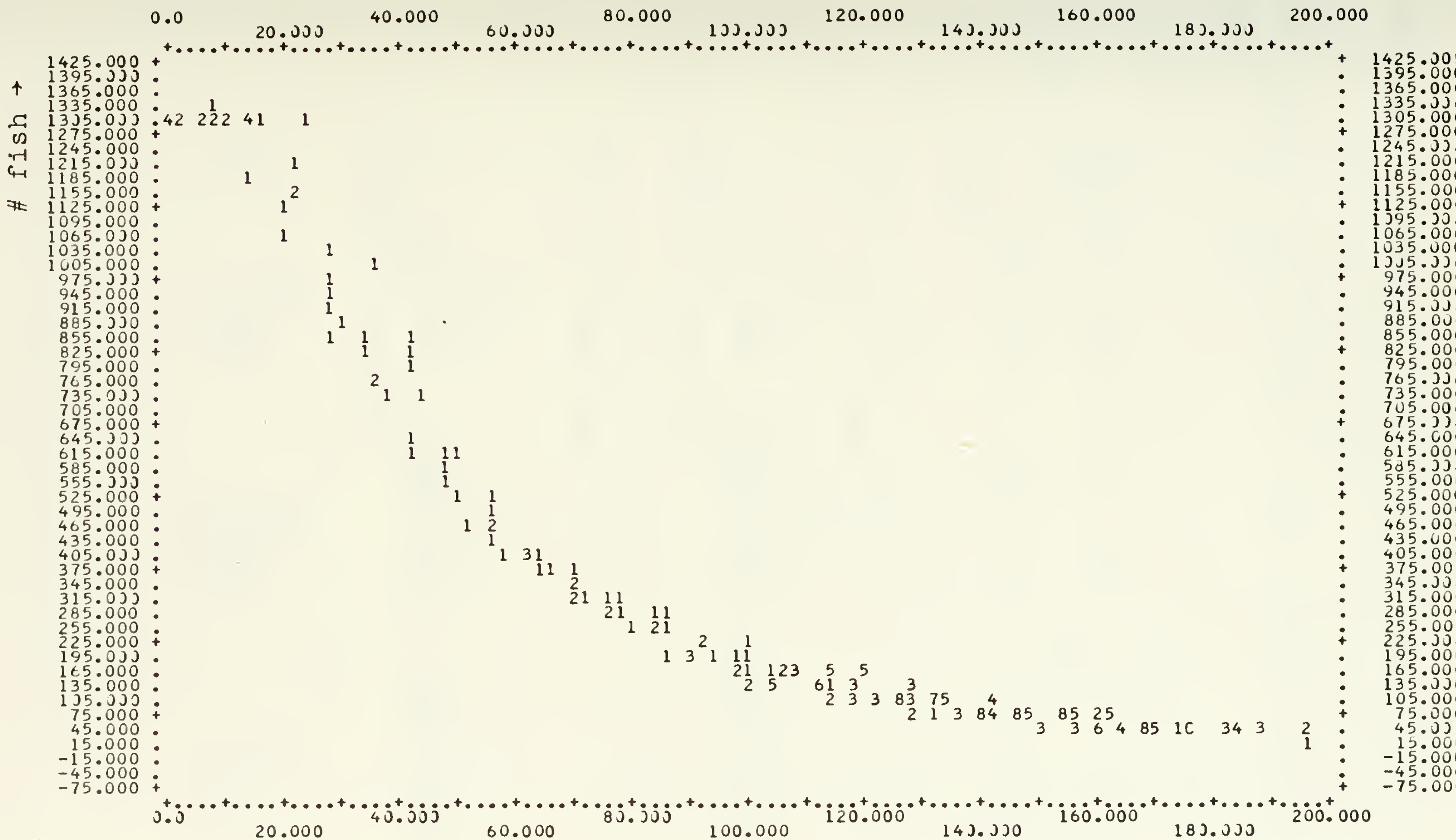


Table B-XII

Scatter Diagram for Coho: Days Reared (Beyond First 20 Days) versus # Fish per Pound, Fresh Water

Table B-XIII

Statistical Information for Plot of Coho: Days Reared (Beyond First 20 Days) versus Ln (# Fish per Pound) and Days Reared (Beyond First 20 Days) versus # Fish per Pound, Fresh Water

REMAINING SAMPLE SIZE= 249

SUMS

1217.6299	29966.0000	54159.0000

MEANS

4.8901	120.3454	217.5060

CROSS PRODUCT DEVIATIONS

	COL. 1	COL. 2	COL. 3
1	209.4552	-10168.8398	54647.7500
2	-10168.8398	505982.8125	-2578525.0000
3	54647.7500	-2578525.0000	17273184.0000

STANDARD DEVIATIONS

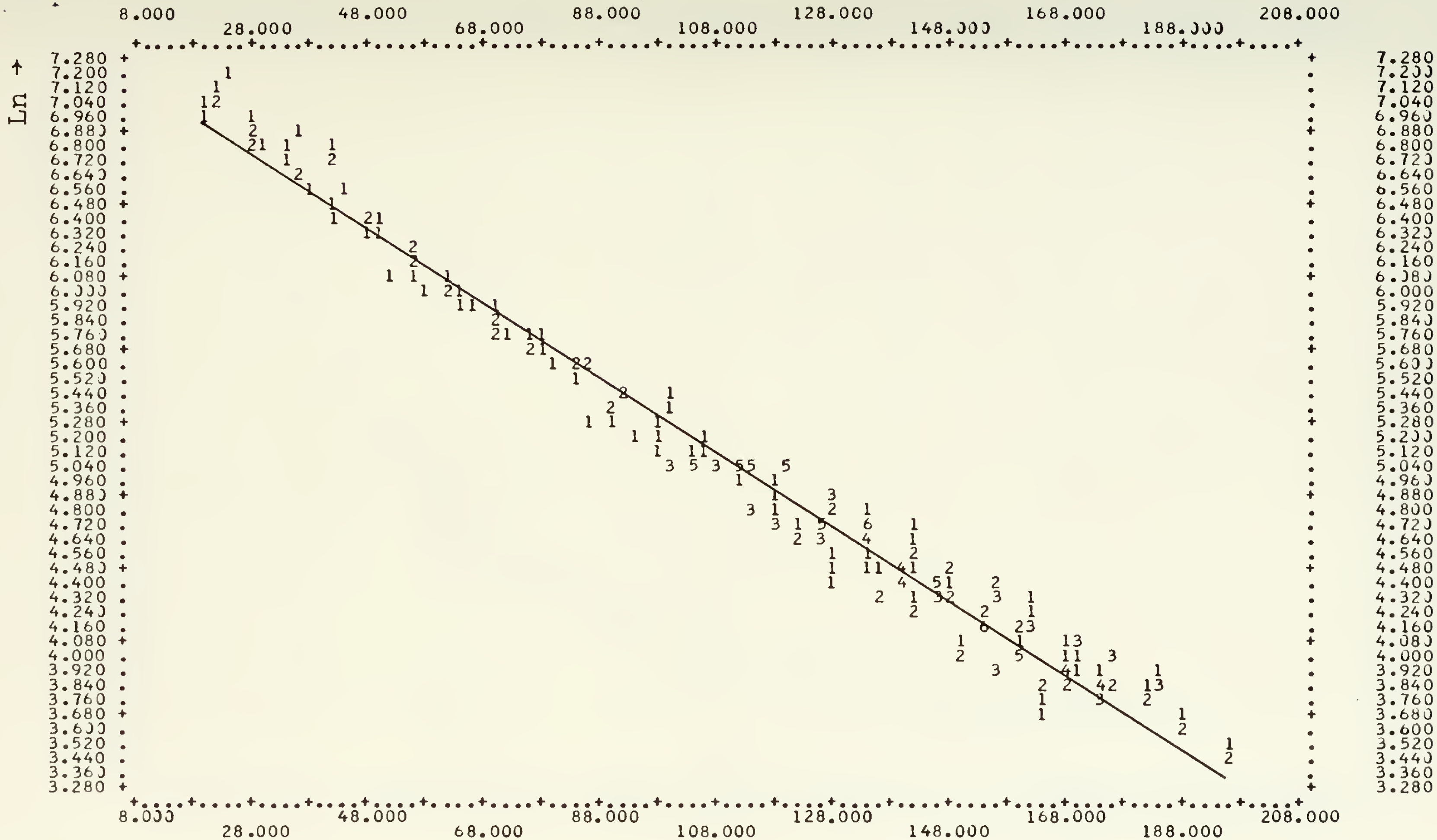
0.9190	45.1692	263.9126

VARIANCE-COVARIANCE MATRIX

	COL. 1	COL. 2	COL. 3
1	0.8446	-41.0034	220.3538
2	-41.0034	2040.2532	-10397.2773
3	220.3538	-10397.2773	69649.8750

CORRELATION MATRIX

	COL. 1	COL. 2	COL. 3
1	1.0000	-0.9878	0.9085
2	-0.9878	1.0000	-0.8722
3	0.9085	-0.8722	1.0000



days →

Table B-XIV

Scatter Diagram and Regression Line for Coho: Days Reared

(Beyond First 20 Days) versus Ln (# Fish per Pound), Fresh Water

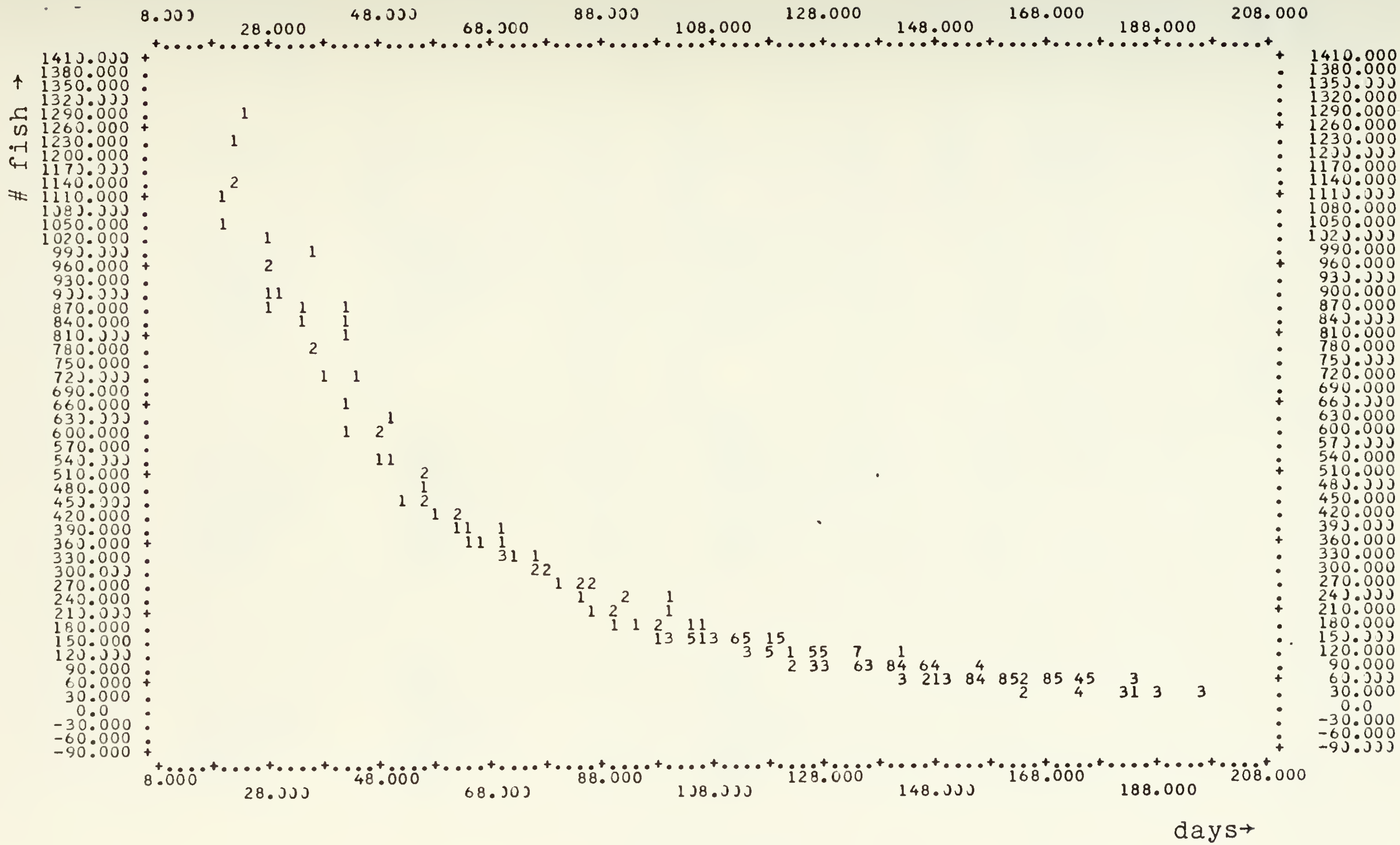


Table B-XV

Scatter Diagram for Coho: Days Reared (Beyond First 20 Days)

versus # Fish per Pound, Fresh Water

Table B-XVI

Statistical Information for Plot of Coho: Days Reared versus Ln (# Fish per Pound) and Days Reared versus # Fish per Pound, Salt Water

REMAINING SAMPLE SIZE= 6

SUMS

10.7610	1494.0000	65.0611

MEANS

1.7935	249.0000	10.8435

CROSS PRODUCT DEVIATIONS

	COL. 1	COL. 2	COL. 3
1	5.2954	-284.7146	53.9020
2	-284.7146	15873.9922	-2865.4602
3	53.9020	-2865.4602	610.8943

STANDARD DEVIATIONS

1.0291	56.3454	11.0535

VARIANCE-COVARIANCE MATRIX

	COL. 1	COL. 2	COL. 3
1	1.0591	-56.9429	10.7804
2	-56.9429	3174.7983	-573.0920
3	10.7804	-573.0920	122.1788

CORRELATION MATRIX

	COL. 1	COL. 2	COL. 3
1	1.0000	-0.9820	0.9477
2	-0.9820	1.0000	-0.9202
3	0.9477	-0.9202	1.0000

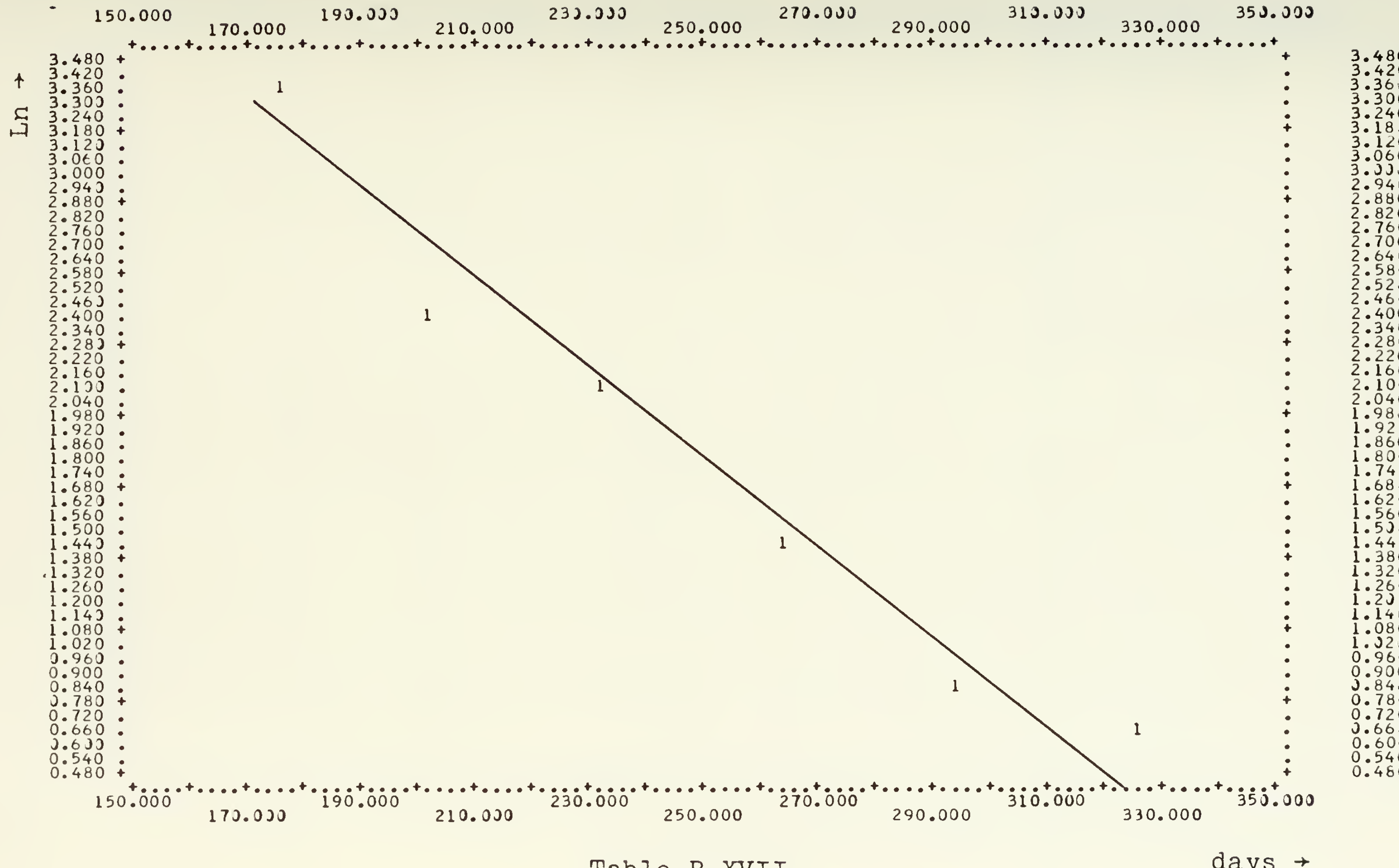


Table B-XVII

Scatter Diagram and Regression Line for Coho, # Days Reared versus Ln (# Fish per Pound), Salt Water

Table B-XVIII

Scatter Diagram for Coho: Days Reared versus # Fish per Pound, Salt Water

Table B-XIX

Bergman Table of Hatchery Fresh Water Pond Maximum Loadings (Pounds of Fish per Cubic Foot per Gallon-per-Minute Inflow)

Temp	Grams/fish						
	.45	.91	4.54	9.08	13.76	18.16	30.27
	Fish/lb.						
°F	1,000	500	100	50	33	25	15
			Coho				
38	3.5	5.0	8.0	11.0	15.0	20.0	25.0
48	2.7	4.0	6.0	10.0	14.0	16.0	18.0
58	2.2	3.0	4.5	7.0	10.0	12.0	15.0
63	1.7	2.0	3.5	5.0	7.0	9.0	10.0
68	.1	.5	1.5	2.0	3.0	3.0	4.0
			Chinook				
38	3.0	4.0	6.0	8.0	11.0	12.0	13.0
48	2.5	3.0	5.0	6.5	9.0	10.0	11.0
58	2.0	2.2	3.5	4.5	6.0	7.5	9.0
63	1.0	1.2	3.0	3.5	4.0	5.0	5.5
68	0.1	0.2	0	0	0	0	0

Washington State Department of Fisheries, Hatchery Division

Table B-XX

Bergman Table of Hatchery Fresh Water Pond Maximum Loadings for Fall Chinook and Coho converted to Pounds of Fish/Cubic Foot at 600 gpm Flow Rate

Temp	Grams/fish						
	.45	.91	4.54	9.08	13.76	18.16	30.27
	Fish/lb.						
°F	1,000	500	100	50	33	25	15
			Coho				
38	.3045	.435	.696	.957	1.305	1.74	2.175
48	.2349	.348	.522	.87	1.218	1.392	1.566
58	.1914	.261	.3915	.609	.87	1.044	1.305
63	.1479	.174	.3045	.435	.609	.783	.87
68	.0087	.0435	.1305	.174	.261	.261	.348
			Fall Chinook				
38	.261	.348	.522	.696	.957	1.044	1.131
48	.2175	.261	.435	.5655	.783	.87	.957
58	.174	.1914	.3045	.3915	.522	.6525	.783
63	.087	.1044	.261	.3045	.348	.435	.4785
68	.0087	.0174	0	0	0	0	0

Table B-XXI

Liao Recommended Fresh Water Pond Loadings for Salmon Converted to Pounds of Fish/Cubic Foot at 600 Gallons-per-Minute Inflow

Temp °F	Grams/fish						
	.45	.91	4.54	9.08	13.76	18.16	30.27
	Fish/lb.						
	1000	500	100	50	33	25	15
38	2.0	2.0	2.0	2.0	2.0	2.0	2.0
48	1.21	1.39	1.89	2.0	2.0	2.0	2.0
58	.65	.74	1.01	1.16	1.25	1.32	1.46
63	.50	.57	.78	.89	.97	1.02	1.13
68	.39	.45	.61	.70	.76	.80	.88

Assumptions:

200 foot hatchery elevation

100% oxygen saturated water entering ponds

4 milligrams oxygen/liter in discharge water, minimum

Maximum loading ≤ 2 pounds of fish per cubic foot.

Year		FC#1	FC#2	Coho#1	Coho#2
1	Eggs, O+M, Labor	1649	1304	1117	755
2	O+M, Labor			18795	18839
	Receipts			-23144	-23144
		14516	13103	-4349	-4305
3	O+M, Labor	7640	9373		
	Receipts	-24819	-24812		
		-17179	-15439		
Net cost		-$1014	-$1032	-$3232	-$3550

Year		FC#1	FC#2	Coho#1	Coho#2
1					
2	Brood			6	3
3	Brood	212	200	246	243
4	Brood, O+M, Labor	1567	1252	1015	658
5	O+M, Labor			18795	18839
	Receipts			-23144	-23144
		14516	13103	-4349	-4305
6	O+M, Labor	7640	9373		
	Receipts	-24819	-24819		
		-17179	-15439		
Net cost		-$884	-$884	-$3082	-$3401

Table C-I. Cost Summary - State/NMFS Mortalities
54¢/lb Return to Grower

Year		FC#1	FC#2	Coho#1	Coho#2
1	Eggs, O+M, Labor	1649	1304	1117	755
2	O+M, Labor	12797	11554	17390	17431
	Receipts			-21411	-21411
				-4021	-3980
3	O+M, Labor	6650	8154		
	Receipts	-21605	-21605		
		-14955	-13451		
Net cost		-$509	-$593	-$2904	-$3225

Year		FC#1	FC#2	Coho#1	Coho#2
1					
2	Brood			6	3
3	Brood	212	200	246	243
4	Brood, O+M, Labor	1567	1252	1015	658
5	O+M, Labor	12797	11554	17390	17431
	Receipts			-21411	-21411
				-4021	-3980
6	O+M, Labor	6650	8154		
	Receipts	-21605	-21605		
		-14955	-13451		
Net cost		-$379	-$445	-$2754	-$3076

Table C-II. Cost Summary - NMFS Mortalities
(54¢/lb Return to Grower)

Year		FC#1	FC#2	Coho#1	Coho#2
1	Eggs O+M Labor	1649	1304	1117	755
2	O+M Labor Receipts	12797	11554	17390 -21803 -4413	17431 -21803 -4372
3	O+M Labor Receipts	6650 -22000 -15350	8154 -22000 -13846		
Net cost		-$904	-$988	-$3296	-$3617

Year		FC#1	FC#2	Coho#1	Coho#2
1					
2	Brood			6	3
3	Brood	212	200	246	243
4	Brood O+M Labor	1567	1252	1015	658
5	O+M Labor Receipts	12797	11554	17390 -21803 -4413	17431 -21803 -4372
6	O+M Labor Receipts	6650 -22000 -15350	8154 -22000 -13846		
Net cost		-$774	-$840	-$3146	-$3468

Table C-III. Cost Summary - NMFS Mortalities
(55¢/lb Return to Grower)

Year		FC#1	FC#2	Coho#1	Coho#2
1	Eggs, O+M, Labor	1649	1304	1117	755
2	O+M, Labor			18795	18839
	Receipts			-25712	-25712
		14516	13103	-6917	-6873
3	O+M, Labor	7640	9373		
	Receipts	-27572	-27572		
		-19932	-18199		
Net cost		-$3767	-$3792	-$5800	-$6118

Year		FC#1	FC#2	Coho#1	Coho#2
1					
2	Brood			6	3
3	Brood	212	200	246	243
4	Brood, O+M, Labor	1567	1252	1015	658
5	O+M, Labor			18795	18839
	Receipts			-25712	-25712
		14516	13103	-6917	-6873
6	O+M, Labor	7640	9373		
	Receipts	-27572	-27572		
		-19932	-18199		
Net cost		-$3637	-$3644	-$5650	-$5969

Table C-IV. Cost Summary - State/NMFS Mortalities
(60¢/lb Return to Grower)

Year		FC#1	FC#2	Coho#1	Coho#2
1	Eggs, O+M, Labor	1649	1304	1117	755
2	O+M, Labor	112797	11554	17390	17431
	Receipts			-23786	-23786
				-6396	-6355
3	O+M, Labor	6650	8154		
	Receipts	-24002	-24002		
		-17352	-15848		
Net cost		-$2906	-$2990	-$5279	-$5600

Year		FC#1	FC#2	Coho#1	Coho#2
1					
2	Brood			6	3
3	Brood	212	200	246	243
4	Brood, O+M, Labor	1567	1252	1015	658
5	O+M, Labor	12797	11554	17390	17431
	Receipts			-23786	-23786
				-6396	-6355
6	O+M, Labor	6650	8154		
	Receipts	-24002	-24002		
		-17352	-15848		
Net cost		-$2776	-$2842	-$5129	-$5451

Table C-V. Cost Summary - NMFS Mortalities
(60¢/lb Return to Grower)

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13. ABSTRACT

A linear programming model of a commercial salmon rearing facility is formulated. A scheme is provided for facility expansion at an optimum rate, maximizing profit to the grower. The variables are the number of fish started in each year and the number of fresh water ponds and salt water pens to construct in each time interval. Constraints are the volumes of facilities required and provided. Cost constraints are included. The model provides the best course of action for facilities expansion based on current knowledge in the salmon mariculture field. The formulation provides for easy updating as technology advances.

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